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Determination of Variability in Leaf Biomass Densities of Conifers and Mixed Conifers Under Different Environmental Conditions in the San Joaquin Valley Air Basin

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

AIR RESOURCES BOARD
Research Division

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Final Report

Contract No. 92-303

Prepared for:

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Abstract

Biogenic emissions of reactive hydrocarbons from vegetation constitute a significant, but as yet undefined, fraction of total hydrocarbon emissions in the San Joaquin Valley Air Basin (SJVAB). Uncertainties in the amounts of reactive hydrocarbons emitted by vegetation have contributed to uncertainties in models of regional ozone formation in the SJVAB. The objective of this research was to provide accurate estimates of foliar biomass per unit area, and the variability associated with those estimates, for the dominant native vegetation of the western slopes of the Sierra Nevada portion of the SJVAB. Biomass sampling plots were established at 29 locations within the dominant vegetation zones of the study area. All of the trees on each 500 m^2 plot were measured for stem and canopy dimensions and branch samples were collected from representative trees. Measurements of intercepted light and soil samples were collected at each plot. Estimates of foliar biomass were made for each plot by three independent methods: 1. regression of tree diameter with leaf biomass; 2. light interception relative to leaf area index; 3. scaling from branch leaf area and biomass to whole canopy leaf area and biomass. Multivariate regression analysis was used to relate these foliar biomass estimates for oak and for conifer plots to a suite of independent predictor variables, including elevation, slope, aspect, temperature, precipitation, and soil chemical characteristics. Results of the regression analyses showed that elevation was the single most useful parameter to predict foliar biomass of conifer-dominated plots. Regression equations for oak plots were generally not significant, possibly because of lack of variability among the oak plots. Based on these results, GIS techniques were employed to calculate foliar biomass of conifer and mixed conifer forest types in 2 x 2 km grid cells across elevational gradients along the western slopes of the Sierras.

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INTRODUCTION AND STATEMENT OF THE PROBLEM

A. The Role of Biogenic Hydrocarbon Emissions

Biogenic emissions of reactive hydrocarbons from naturally-occurring vegetation constitute a significant but as yet undefined fraction of total volatile hydrocarbons in the San Joaquin Valley Air Basin (SJVAB). These biogenic hydrocarbons can contribute to photochemically-generated oxidant air pollution in both urban and rural areas (Altschuller 1983; Chameides *et al.* 1988; Dimitriades 1981). Inventories of biogenic hydrocarbon emissions are crucial to complete emission source inventories in the SJVAB and to assist in modeling studies of photochemical oxidant pollution formation and dispersion in the SJVAB. Compilation of a complete inventory of biogenic hydrocarbon emissions for an air basin has two key components:

1. Field and laboratory studies of rates of reactive hydrocarbon emissions from the dominant vegetation types in the area.
2. Estimates of foliar biomass densities across environmental gradients of the dominant vegetation types, so that rates of natural hydrocarbon emissions can be converted to amounts of hydrocarbon emitted on a temporal and regional scale.

This report will address the need for a detailed inventory of leaf biomass densities by providing estimates of the variability of foliar biomass for major vegetation types across environmental gradients.

B. Dominant Vegetation Types of the Sierras

Previous studies of hydrocarbon emissions from natural vegetation have shown that oaks (*Quercus* spp.) and conifers, particularly pines (*Pinus* spp.) are major sources of volatile reactive hydrocarbons (Lamb *et al.* 1985). The principal hydrocarbon emitted from oaks and other hardwoods is isoprene while α- and β-pinene are the major components of hydrocarbon emissions from conifers (Lamb *et al.* 1985). This suggests that the oak woodlands of the Sierra foothills and the conifer and mixed conifer forest zones on the western slopes of the Sierra

Nevada may be significant sources of reactive hydrocarbons that may influence photochemical oxidant formation in the SJVAB. Other major types of vegetation coverages that could also contribute to biogenic hydrocarbon emissions, such as agricultural crops, urban landscaping, and grasslands (Winer *et al.* 1990) will not be considered in this report.

The conifer and mixed conifer forest zones in the Sierras extend from approximately 1500 m to 2500 m in elevation. Within the broad conifer and mixed conifer zones, the distribution and density of individual tree species are controlled by elevational and soil moisture gradients (Fig. 1). Slope, aspect, soil edaphic properties, fire history, logging and other disturbances also play major roles in determining plant distribution and biomass (Rundel *et al.* 1977). The lower dryer slopes of the Sierras are dominated by ponderosa pine (*Pinus ponderosa* Laws.). In much of the ponderosa pine zone logging and other disturbances have led to considerable replacement of pine with other tree species, including white fir [*Abies concolor* (G. & G.) Lindl.] and incense cedar [*Calocedrus decurrens* (Torr.) Florin]. On the more mesic upper slopes, the mixed conifer forest type prevails, whose dominant species include ponderosa pine, sugar pine (*P. lambertiana* Doug.), white fir, incense cedar, and California black oak (*Quercus kelloggii* Newb.). Groves of giant sequoia [*Sequoiadendron giganteum* (Lindl.) Buckh.] dominate slopes or draws where soil moisture is abundant, and Jeffrey pine (*P. jeffreyi* Grev. & Balf.) dominate exposed, rocky ridge crests. Above the mixed conifer zone, areas of red fir (*Abies magnifica* Murr.) occupy more mesic sites and lodgepole pine [*P. contorta* var. *murryana* (G. & B.) Critch.] are found on the rocky, exposed sites (Sudworth 1967).

Although the original scope of work of this project was confined to the conifer and mixed conifer zones on the western slopes of the Sierras, the oak woodlands of the foothills, below the ponderosa pine belt, were also surveyed. The oak woodlands were included because of the importance of isoprene emissions from oaks and other hardwoods. Isoprene emission rates from oaks can be 10 or more times greater than rates of terpene emissions from pines (Tanner and Zielinska 1994). So, in consultation with ARB personnel, the original scope of work was expanded to include estimates of foliar biomass from oak savannas and oak woodlands in the foothills. The pristine oak woodlands of the Sierra foothills have mostly been converted to grazing lands, but the remaining dominant trees include blue oak (*Quercus douglasii* Hook. & Arn.), canyon oak (*Q. chrysolepis* Liebm.), and gray pine (*P. sabiniana* Doug.). Several other

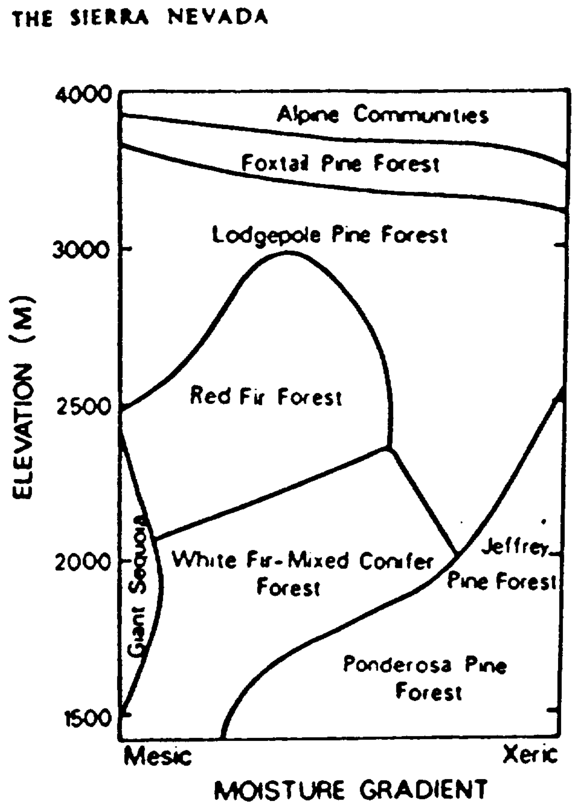

Figure 1. Major vegetation types in the Sierra Nevada in relation to moisture and elevational gradients [adapted from Rundel *et al.* (1977)].

species of oaks, including valley oak (*Q. lobata* Nee) and interior live oak (*Q. wislizeni* A. deC.), are now highly localized in distribution.

C. Methods for Estimating Foliar Biomass

1. Allometric Relationships

The only technique for the direct measurement of foliar biomass and leaf area is the destructive harvesting of the tree, removal of all the foliage, measuring the leaf area and weighing the mass of leaves. This method is clearly impractical for the measurement of large numbers of trees, so foresters have devised sampling techniques that rely on non-destructive measurements of standing trees. The traditional technique involves the establishment of allometric relationships between tree diameter or sapwood area and leaf mass (Brown 1978, Westman 1987). This relationship is determined by the destructive harvesting of a limited number of trees over a wide range of diameters and measurement of leaf area and leaf biomass for the entire crown or for representative branches. Regression equations between tree diameter at breast height (DBH) and leaf area and mass have been published for a number of tree species, including several species in the study zone in the Sierras (Brown 1978, Westman 1987). The primary advantages of this technique are that it is based on actual tree measurements and that measurement of DBH is quick and accurate so that large numbers of trees can be sampled. The major disadvantage of this procedure is that the regression equation between DBH and leaf biomass is based upon a limited number of trees from a specific geographical area. Thus the equations may not represent the unique characteristics of the trees from a particular sampling plot nor do the allometric regression equations capture the potential variability of the relationship between DBH and leaf biomass across environmental gradients.

2. Proportional Relationships

This technique employs the proportional relationship between the volume of foliage on branches sampled from individual trees and the volume of foliage in the tree crown as a whole. The leaf mass and area from the branch samples are measured and the percent of the whole tree crown represented by the branch is calculated, and the data from the branch samples are scaled up to estimate the tree crown as a whole. The advantage of this procedure is that it is based upon easily-obtainable measurements of crown volumes from large numbers of trees. The major disadvantage is that very large trees cannot be sampled because even the lowest branches cannot be reached. In addition, tree crown geometry is assumed to be symmetrical, which may not be valid for high density plots with overlapping crowns. Further details of this technique are given in Task 2, Section A.

3. Light Interception

This technique for estimation of foliar biomass involves measurement of the amount of incident photosynthetically-active solar radiation transmitted through the tree canopy, in comparison with the amount of light measured in an open area. The amount of light intercepted by the tree canopy has been shown to be proportional to the projected and total leaf area of the canopy (Lang 1991, Pierce and Running 1988). Leaf area and leaf area index (LAI) can be calculated from published equations and leaf biomass can be calculated from the relationship between specific leaf area and leaf dry weight. Specific details of this technique will be given in Task 2, Section A. This method has the advantage that measurements of transmitted light can be made relatively quickly, so a large number of sample points can be measured over a range of environmental conditions. Second, estimates of foliar biomass based upon transmitted light can be directly compared with biomass estimates derived from reflected light, as in Thematic Mapper data (see Section C.4. in Introduction). The major disadvantage of this technique is that leaf area estimates are derived from equations using extinction coefficients that have not been completely validated either theoretically or empirically (Lang and Xiang 1986). The advantages and limitations of the light intercept method for estimating LAI have been discussed in a number of recent publications (Norman and Campbell 1989).

4. Remote Sensing Techniques

Two previous estimates of foliar biomass in the SJVAB (Engineering-Science 1990, Tanner *et al.* 1992) relied primarily on remote sensing data derived from satellite imagery supplemented with aerial photography and existing vegetation classification databases. Data from the Landsat Thematic Mapper was processed using a vegetation band ratio called the Normalized Difference Vegetation Index (NDVI). The NDVI has been shown to differentiate vegetation types and to provide estimates of growth and productivity based upon chlorophyll reflectance measurements (Becker and Chandury 1988, Teng 1990). Once the boundaries and geographical extent of the different classes of vegetation were delineated, a specific location within a vegetation classification unit was selected and the foliar biomass was estimated for the major plant species within the unit.

The major disadvantage of this technique is that biomass estimates within a vegetation type were based upon samples not necessarily collected within that unit, so that significant discrepancies were reported between leaf biomass estimates from the model and actual measurements of leaf biomass from sampling in the field (Tanner *et al.* 1992). In addition, the remote sensing data cannot be used to provide estimates of the variability of foliar biomass as influenced by environmental factors. Environmental gradients can vary widely over relatively short distances, particularly in mountainous terrain where slope, aspect, soil water, and soil type can change rapidly with short changes in elevation. Estimates of foliar biomass based upon "typical" units of a vegetation classification type cannot be used to estimate the error associated with these rapidly-changing environmental gradients.

D. Objectives

The objective of this research was to provide estimates of foliar biomass per unit area, and the variability associated with those estimates, for the dominant vegetation of the foothills and western slopes of the Sierras in the SJVAB portion of Tulare, Madera, Fresno, and Kern Counties. Within each sampling plot foliar biomass was measured by three independent techniques, which provided an estimate of the error associated with the biomass data. Foliar biomass data from the sampling plots were aggregated on a regional scale using a multivariate regression model that related foliar biomass to a suite of environmental variables. The regression analysis provided confidence limits on the foliar biomass estimates and indicated the statistical significance of the various environmental parameters as predictors of variations in biomass densities across the study area.

TASK 1
SELECTION OF VEGETATION SAMPLING SITES THAT REFLECT THE VARIABILITY OF THE ENVIRONMENTAL CONDITIONS THAT INFLUENCE TREE GROWTH

A. Methodology

The initial criteria used in the process of site selection are listed in Table 1. These criteria were selected by reference to the literature on the distribution of dominant vegetation types in the Sierras, by reference to silvicultural manuals which describe the range of growing conditions for each tree species, and by consultation with members of the US Forest Service with extensive field experience in the Sierras. The primary attributes of each site were the dominant vegetation type, and the slope, aspect, and elevation. The slope, aspect, and elevation define to a large extent the environmental conditions under which the vegetation is growing and thus define the potential biomass of the vegetation.

Specific criteria for the preliminary site selection process included the dominant vegetation types of ponderosa pine, Jeffrey pine, and white fir, elevation ranges of 1500 to 3000 m at 500 m increments, slopes of 0 to 12 and 12 to 24 degrees, and northern (0 to 90, 270 to 360 degrees) and southern (90 to 270 degrees) aspects. Potential candidate sampling plots were generated using ARC/INFO spatial analysis techniques on the following databases: the California Digital Elevation Model (DEM) at a resolution of 250 m, Desert Research Institute's enhanced version of CALVEG, and coordinates of county lines, the outline of the San Joaquin Valley Air Basin, and major roads from the Teale Data Center. All coverages were projected to Lambert coordinates.

The California DEM was resampled at a resolution of 2000 m to generate a master grid, 2 km by 2 km, whose coverage was compatible with Radian's Biogenic Emission Inventory Model. Missing cell values originating from missing USGS data points for some areas were estimated using focal point mean procedures calculated from all adjoining grid cells with data values. Polygon coverage was generated from the 2 x 2 km grid for intersection with other databases for subsequent site selection. The polygon coverage was resampled and additional coverages were generated based upon specified ranges in elevation for each vegetation type.

Table 1. Summary of plot characteristics used in the classification of potential biomass sampling sites in the Sierras.

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1. Confine sampling sites to the San Joaquin Valley Air Basin portion of the western Sierras in Tulare, Madera, Fresno, and Kern Counties.

2. Dominant vegetation types:

   a. Ponderosa pine/mixed conifer forest - CALVEG type no. 8

   b. White fir/mixed conifer forest - CALVEG type no. 15

   c. Jeffrey pine forest - CALVEG type no. 34

3. Elevation:

   a. Ponderosa type:

      i. 1500-2000 m
      ii. 2000-2500 m

   b. White fir type:

      i. 1500-2000 m
      ii. 2000-2500 m

   c. Jeffrey pine type:

      i. 2000-2500 m

4. Slope:

   a. Flat to moderate: 0-12 degrees

   b. Moderate to severe: 12-24 degrees

5. Aspect:

   a. North-facing: 270 W - 90 E

   b. South-facing: 90 E - 270 W

6. Accessible by roads or trails; not on private lands or in wilderness areas.

Aspect was determined for each grid by calculating the down-slope direction of maximum rate of change from each cell to its neighbors. The values of the output grid were the compass directions of the aspect, in which 0 degrees = north, and which progressed to 360 degrees in a clockwise direction. A polygon coverage was generated from the grid and then the grid was resampled to determine the location of north and south-facing aspects.

An output slope grid was calculated as degree of slope, in which 0 degrees = level and 90 degrees = vertical. The range of mean slope values for individual 2 x 2 km cells within the study area varied from 0 to 24 degrees. The steeper slopes expected within a mountainous region were not expressed within the mean slope values because averaging over a 2 x 2 km grid cell masked these extreme slope values. A polygon coverage was generated from the grid and resampled to identify areas with slopes of 0 to 12 and 12 to 24 degrees.

To produce the final selection of potential sampling sites the reduced coverages described above, representing the geographic distribution of the dominant vegetation types and the specified elevations, slopes, and aspects, were intersected to compute the specific grid cells common to the specified parameters. These cells have been displayed in a series of figures, representing the geographical range within the study area of potential sampling sites that share a specified set of parameters. In Figure 2 the dominant vegetation of the entire SJVAB is shown and the overall coverage of ponderosa pine, Jeffrey pine, and white fir are shown throughout their range in the southern Sierras. The dominant vegetation types of the Sierra Nevada portion of the SJVAB are shown in Figure 3. The clear elevational gradient, from the oak-dominated foothills, to ponderosa pine-dominated lower slopes, to white fir-dominated mixed conifer forests on middle slopes, is well-illustrated in this figure. Figure 4 shows the distribution of the 2 x 2 km grid cells representing ponderosa pine growing at elevations between 2000 to 2500 m, on 0 to 12 degree slopes with south facing aspects. Figure 5 represents white fir growing between 1500 to 2000 m, on 0 to 12 degree slopes with south-facing aspects. Figure 6 shows white fir growing between 2000 to 2500 m on 0 to 12 degree slopes with south-facing aspects. Similar maps were prepared for all other combinations of vegetation type, elevation, slope, and aspect.

In the original Request for Proposals and in the Technical Plan submitted in response to that RFP, the scope of the project was confined to conifer and mixed conifer forest types of the

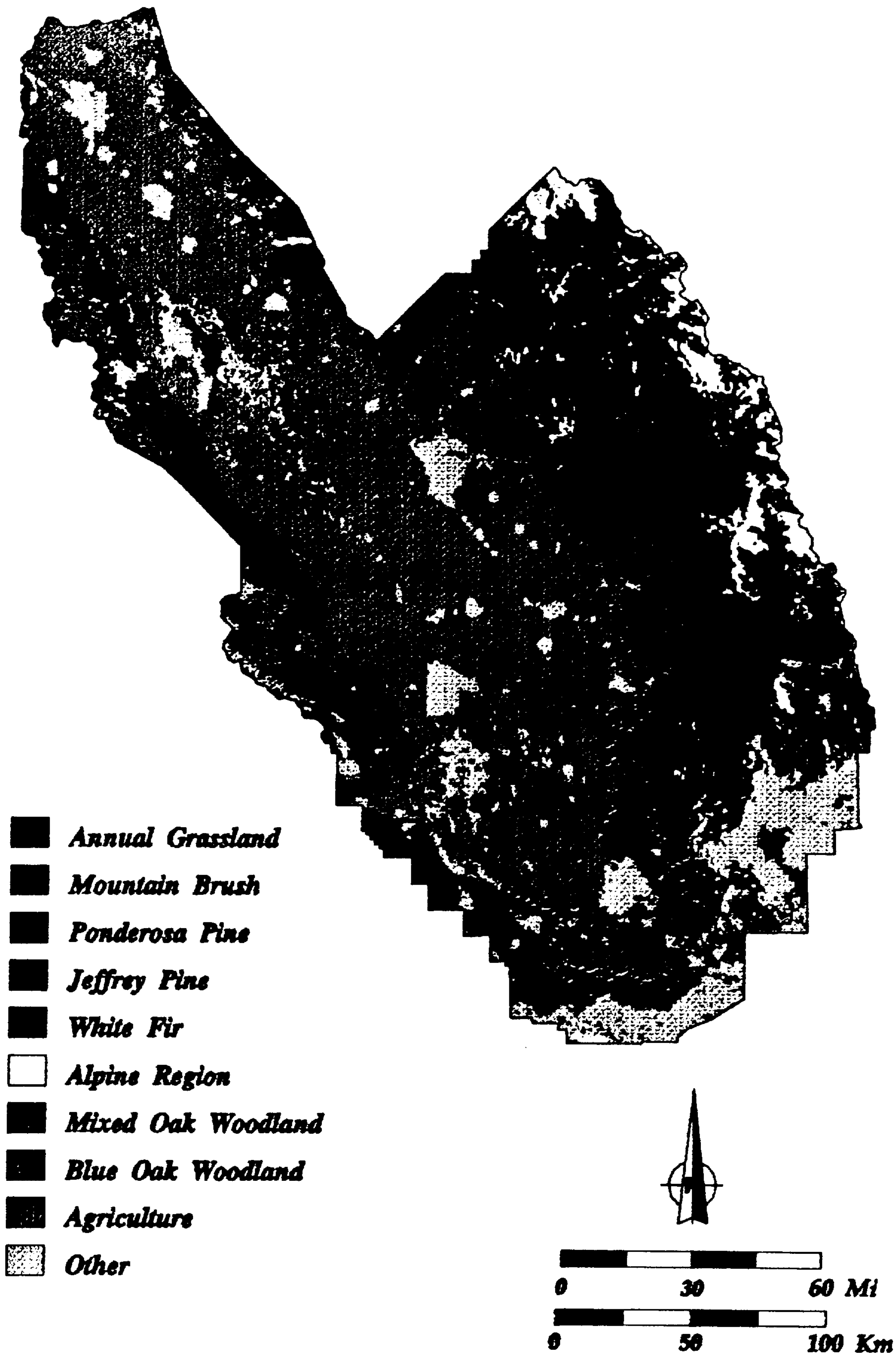


Figure 2. Dominant vegetation types of the SJVAB, based upon CALVEG as modified by the Desert Research Institute.

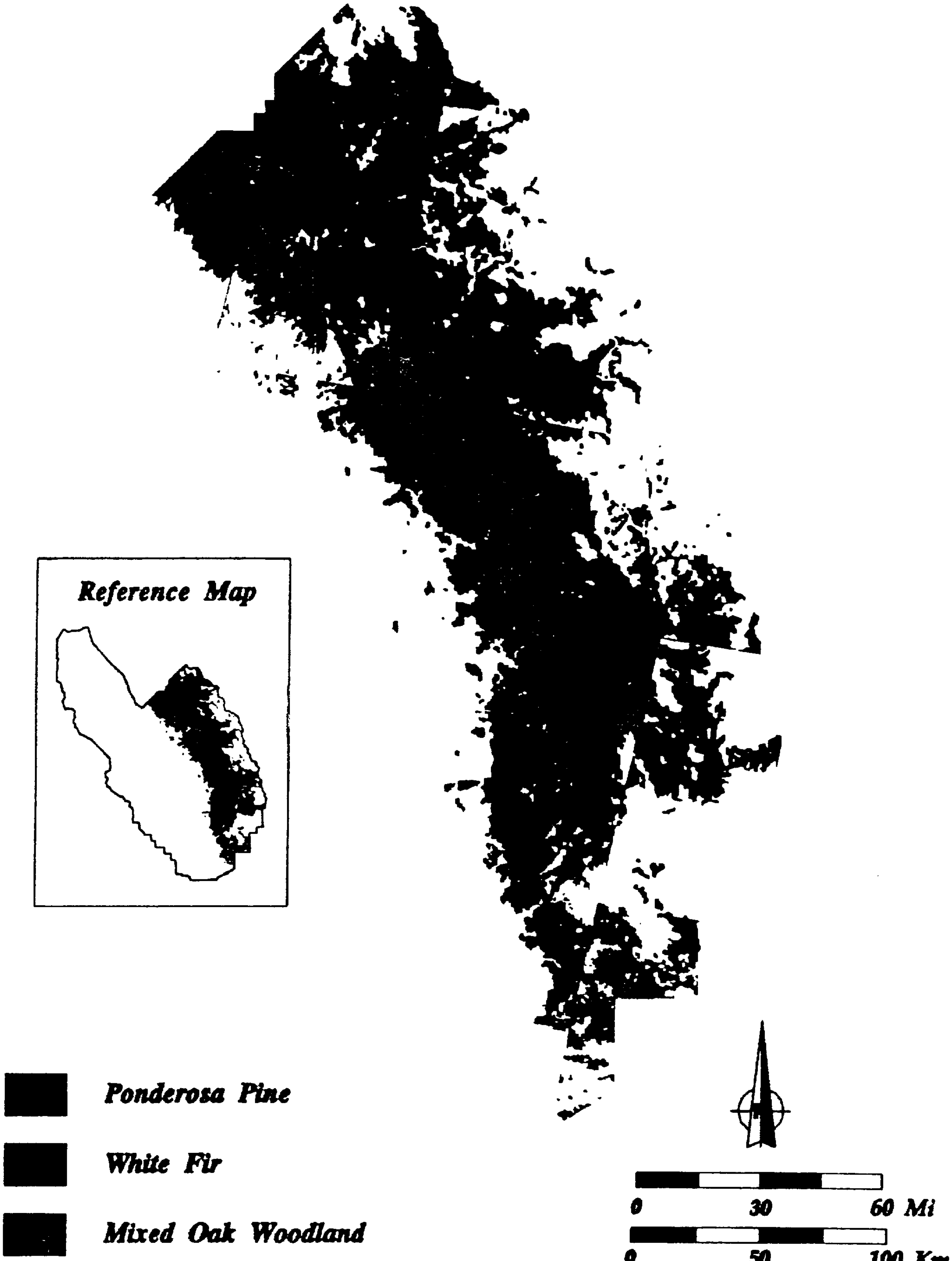


Figure 3. Forest zones of the lower and middle slopes of the SJVAB portion of the Sierras, dominated by oak savannas and woodlands (foothills), ponderosa pine zone (lower slopes), and white fir dominated mixed conifer forests (middle slopes).

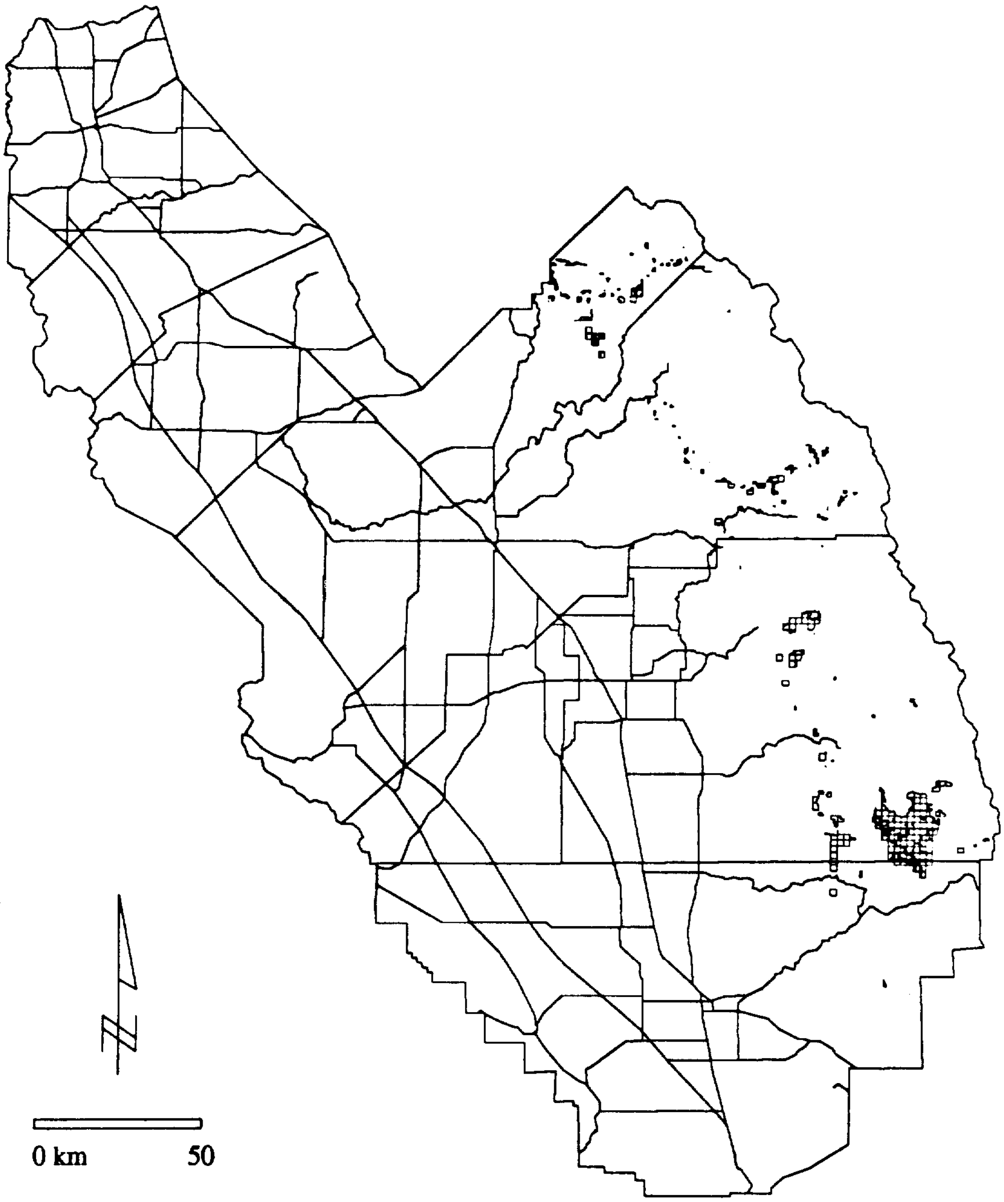


Figure 4. Two x two kilometer grid coverages of ponderosa pine dominated areas located between 2000 to 2500 m elevation on south-facing 0 to 12 degree slopes in the Sierras.

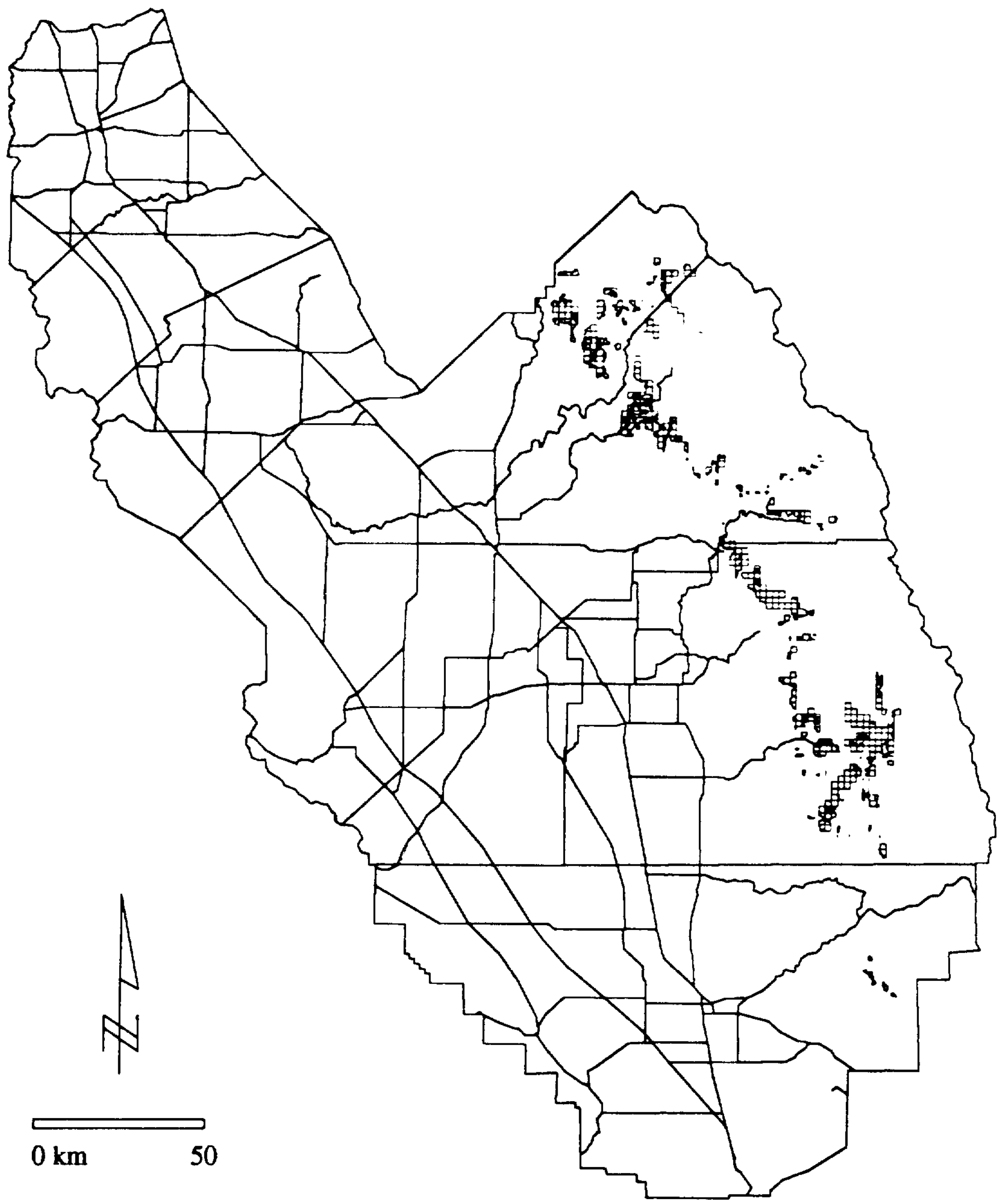


Figure 5. Two x two kilometer grid coverages of white fir dominated areas located between 1500 to 2000 m elevation on south-facing 0 to 12 degree slopes.

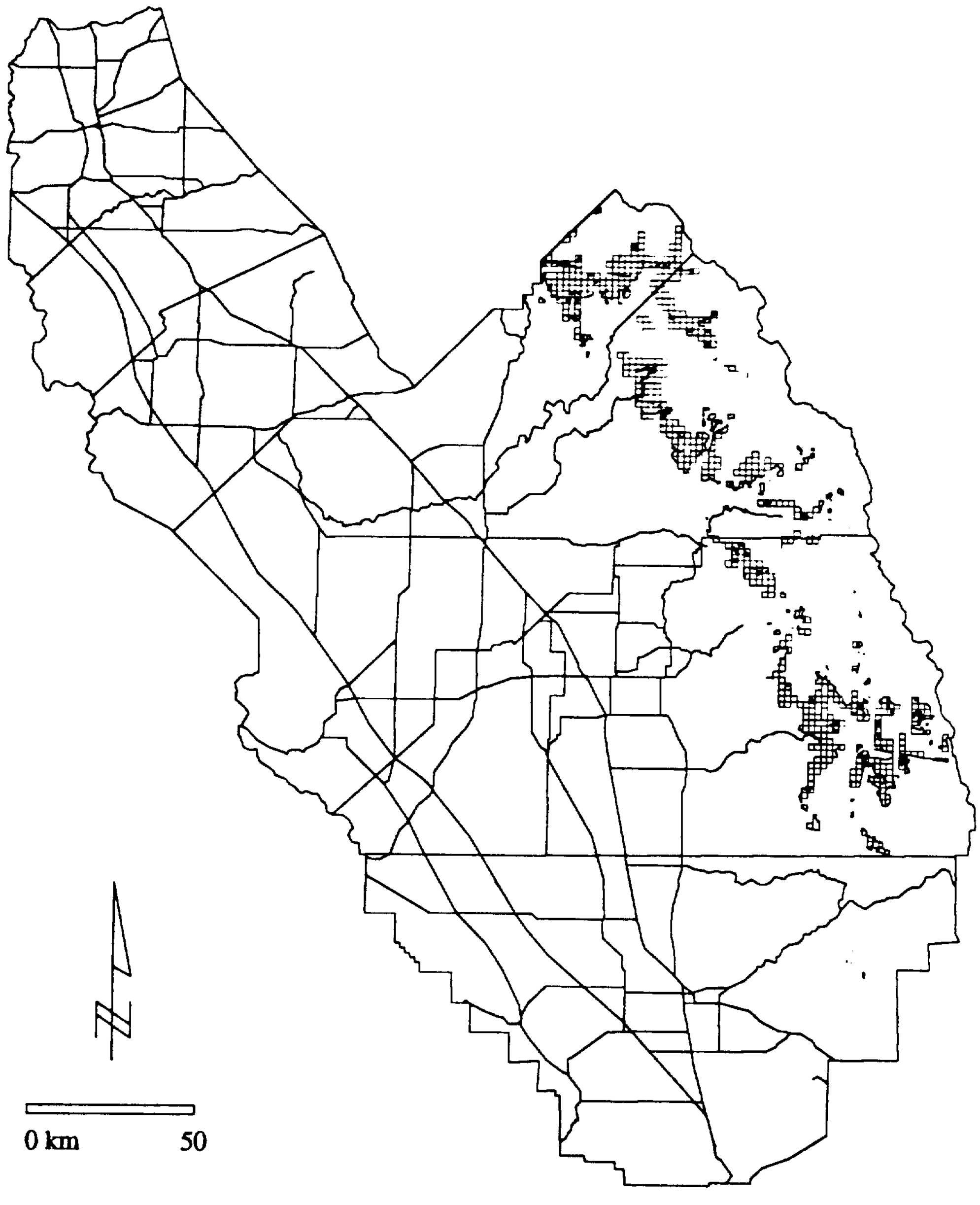


Figure 6. Two x two kilometer grid coverages of white fir dominated areas located between 2000 to 2500 m elevation on south-facing 0 to 12 degree slopes.

western slopes of the Sierras. The initial protocol for selection of sites (Table 1) reflected this restriction. Later, in consultation with CARB, the scope of work was expanded to include biomass sampling plots in the mixed oak woodland vegetation type of the Sierra foothills (Fig. 2). This vegetation type has largely been converted to agricultural use, primarily orchards and pasturelands, so only a limited number of plots were located in the oak zone.

B. Results

Between 7 July and 7 September 1993, a total of 29 vegetation sampling plots were established from the Kernville/Lake Isabella area at the southern end of the Sierras to the Madera/Mariposa county line at the northern limit of the SJVAB. The locations and a brief description of each plot is given in Table 2. The site characteristics for each plot, including dominant vegetation type, GIS coordinates, elevation, slope, and aspect are given in Table 3. The location of each sample plot relative to its position on an elevational gradient from the foothills to the middle slopes of the western Sierras is shown in Figure 7.

Table 2. Location of biomass sampling plots and a description of the dominant and understory vegetation at each plot.

Plot 1.	Greenhorn Mts., 2.2 mi. S of Alta Sierra on Rancheria Rd., S facing slope dominated by second-growth incense cedar, white fir, and California black oak, with a few scattered large ponderosa pine; understory is mostly seedling incense cedar.
Plot 2.	Greenhorn Mts. 1.3 mi. SE of Alta Sierra, N facing slope dominated by incense cedar and white fir, similar to Plot 1.
Plot 3.	NE of Kernville, S facing. Jeffrey pine dominated, also incense cedar and white fir; understory is composed of a few California black oak.
Plot 4.	Similar to plot 3, N facing. Jeffrey pines, white fir, and incense cedar.
Plot 5.	Camp Nelson area, dirt road 1.4 mi. E of Redwood Drive on Hwy. 190. Ponderosa pine and Jeffrey pine dominated; understory mostly seedling and sapling incense cedar.
Plot 6.	Holby Meadow Road, along Western Divide Hwy. above 2000 m, wide, flat ridge-top dominated by white fir; understory consists of white fir seedlings.
Plot 7.	Balch Park Rd. 8.3 mi. E of intersection with Yokohl Rd. at 1500 m. Ponderosa pine dominated, mixed with black oak and incense cedar; understory is also incense cedar seedlings.
Plot 8.	Hospital Rock Picnic Area, along Hwy. 198 in Sequoia National Park; S facing slope at 1000 m in oak zone, dominated by valley oak (*Quercus chrysolepis*) with buckeye (*Aesculus californica*) sub-dominant; understory consists of grasses and annual plants.
Plot 9.	Hwy 198, 2.2 mi. E of Plot 8 at 1050 m. Open oak plot dominated by valley oak, black oak and scattered blue oak (*Quercus douglasii*); understory is scattered buckeye, *Rhamnus sp.* and *Umbellularia californica*.
Plot 10.	White fir dominated; 6.0 mi N of plot 9 on General's Highway; S facing, mid-slope. Understory is western flowering dogwood (*Cornus Nuttallii*).
Plot 11.	Wolverton Ski Area; Pack Animal Corral; 1.2 mi N of Gen Sherman parking lot. SW facing slope dominated by large white fir; understory is white fir saplings.

Table 2 (continued)

Plot 12.	Montecito-Sequoia Lodge road; just past bridge over first creek, 100 m S of road. Red fir (*Abies magnifica*) dominated. Red fir has dark reddish bark, much darker than white fir; red fir needles have two faint white lines on upper surface, white fir lacks these lines. One large lodgepole pine (*Pinus contorta*) has "corn flakes" bark. Understory is seedling white and red firs and Ribes (currants).
Plot 13.	Lodgepole pine. Big Meadows road, 100 m E of "Starlight Trail" road 14S14. 100% lodgepole pine, understory is sparce lodgepole pine. Flat ridge-top.
Plot 14.	Pack animal saddle area, 0.15 mi N of turnoff to Gen. Grant tree; S-facing, flat ridge-top. Large sugar pines (*Pinus lambertiana*) mixed with red fir and sapling sugar pines; understory is Rosa sp.
Plot 15.	Jeffrey pine (*Pinus jeffreyi*), 0.1 mi S of turnoff to Stony Creek Lodge. 100% Jeffrey pine, sparce understory is also Jeffrey pine.
Plot 16.	Mackenzie Ridge, Ponderosa pine dominated. Plot has large ponderosa pines and smaller incense cedar, understory is young white fir and also Ceanothus and Ribes. N-facing, near ridge top. 3.9 mi from Hwy 180, along left fork of turnoff to YMCA Sequoia Lake Camp, along road 13S67 until int. with 13S78, 50 m down 13S78, then 10 m down slope (over rocky ledge).
Plot 17.	Mt. Home State Forest. Giant Sequoia/white fir dominated. Understory is a few white fir seedlings and Ribes. 20.3 mi from int. of Balch Park Rd. and Yokohl Rd. 200 m upslope, NW facing, mid-slope.
Plot 18.	Shaver Lake, junction of Peterson Road and Big Creek Road. Ponderosa pine dominated, with mixture of sugar pine, incense cedar and California black oak; understory of pine and oak saplings and manzanita.
Plot 19.	Shaver Lake, Soaproot Saddle Road, 2.6 mi E of Plot 18. Dense ponderosa pine stand; understory mostly manzanita.
Plot 20.	Hwy 168 N of Shaver Lake, at road 8S12. Mixture of large red and white firs on N facing slope; understory of fir saplings.
Plot 21.	Hwy 168 at Tamarisk Ridge. Mixture of red and white firs on S facing slope.
Plot 22.	Shaver Lake, Dinkey Creek Rd. at road 10S87. Dense Jeffrey pine stand; understory is *Ribes spp*. and manzanita.

Table 2 (continued)

Plot 23.	Dinkey Creek Rd., 0.4 mi along road 10S76. Mixed conifer forest, ponderosa and sugar pines, incense cedar and a few white firs; understory of white fir and incense cedar seedlings.
Plot 24.	Bass Lake. Ponderosa pine dominated, with a few California black oak; understory of incense cedar and manzanita.
Plot 25.	Hwy 41 at Madera/Mariposa county line. Mixed conifer forest, ponderosa and sugar pines; understory of incense cedar and white fir saplings.
Plot 26.	San Joaquin Experimental Range, California State University, Fresno, 1.2 miles E of Highway 41 on Rd. 8063, 75 m S of road, S facing slope (3°), rolling topography. Savannah dominated by scattered canyon oak (*Quercus chrysolepis*), blue oak (*Quercus douglasii*), and occasional grey pine (*Pinus sabiniana*) with an understory of perennial grasses.
Plot 27.	E of Bakersfield on Breckenridge Rd, turn north on Democrat Rd, 1.1 mi., 100 E of road, SW facing 13° slope, rolling topography. Savannah dominated by blue oak (*Quercus douglasii*) with an understory of perennial grasses.
Plot 28.	3.5 mi E of California Hot Springs Rd on M-56, then N on Mtn Rd #52 for 2.3 mi., 50 m W of road, N facing 18° slope, rolling topography. Savannah dominated by blue oak (*Quercus douglasii*) with an understory of perennial grasses.
Plot 29.	0.5 mi. S of Ruth Hill Rd. on Ennis Rd. on E side of the road, S facing 14° slope, rocky rolling topography. Ruth Hill Rd. intersects with Highway 180 1 mi. E of Highway 63 in the Squaw Valley area. Savannah dominated by blue oak (*Quecus douglasii*) with an understory of perennial grasses.

Table 3. Site characteristics for biomass sampling plots in the SJVAB.

Plot No.	Dominant Vegetation	Lat.	Elevation, meters	Slope, degrees	Aspect, degrees
1	cedar/white fir	35.7	1950	9	160
2	cedar/white fir	35.7	1650	12	35
3	mixed conifer	35.9	2060	18	245
4	white fir	35.9	2150	17	0
5	cedar/white fir	36.2	1750	18	190
6	white fir	36.1	2200	6	50
7	ponderosa pine	36.3	980	15	180
8	oak woodland	36.5	950	24	45
9	oak woodland	36.6	1400	20	180
10	white fir	36.6	1500	17	0
11	white fir	36.6	2200	10	230
12	red fir	36.7	2150	5	130
13	lodgepole pine	36.7	2300	5	180
14	red fir	36.7	2200	8	195
15	Jeffrey pine	36.7	2100	10	150
16	ponderosa pine	36.7	1600	15	40
17	mixed conifer	36.2	1900	16	330
18	ponderosa pine	37.0	1375	0	210
19	ponderosa pine	37.0	1325	2	145
20	red/white fir	37.2	2200	10	220
21	red/white fir	37.2	2275	12	195
22	Jeffrey pine	37.1	2000	2	200
23	ponderosa pine	37.1	1800	8	215
24	ponderosa pine	37.3	1100	18	30
25	ponderosa pine	37.3	1400	11	180
26	oak woodland	37.1	450	3	210
27	oak woodland	35.4	950	13	120
28	oak woodland	35.9	700	18	0
29	oak woodland	36.7	400	14	200

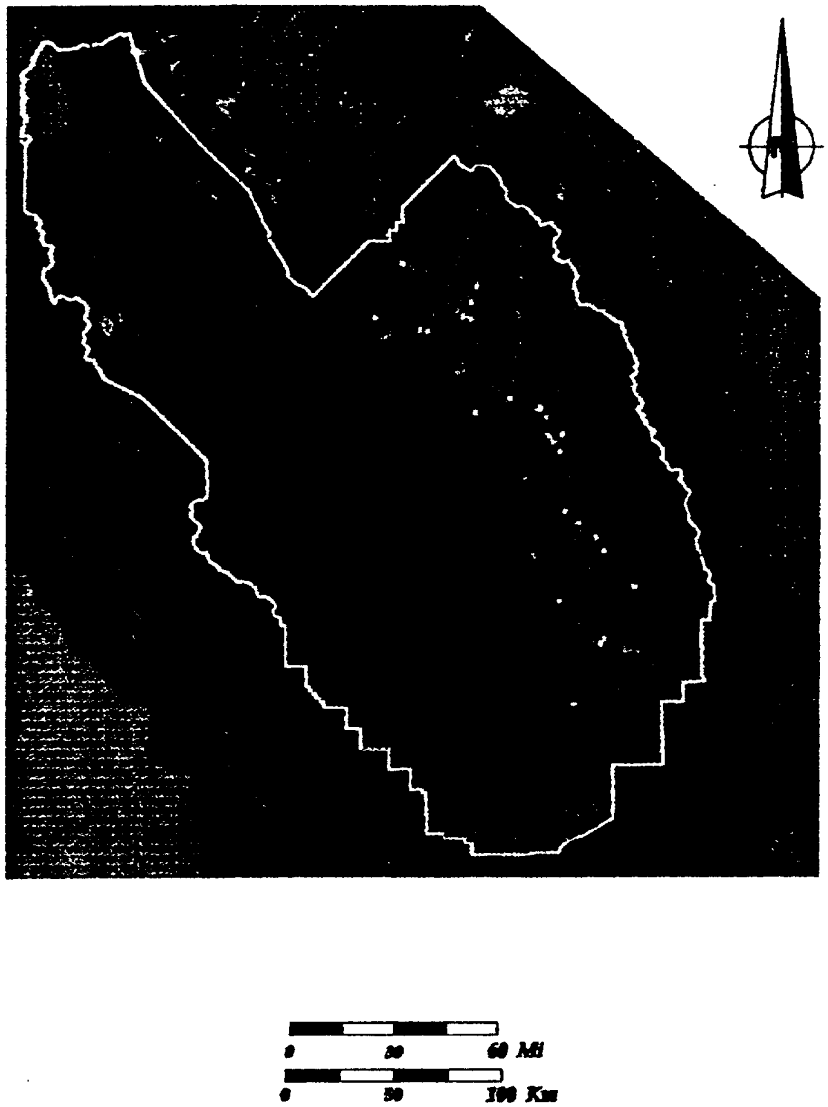


Figure 7. Location of biomass sampling plots within the SJVAB (outline) relative to elevational gradients in the Sierras.

TASK 2
MEASUREMENT OF LEAF BIOMASS DENSITIES AND ENVIRONMENTAL VARIABLES IN THE FIELD

A. Methodology

1. Tree Mensuration and Collection of Branch Samples

At each of the vegetation sampling sites a 500 m^2 plot was established in areas that were least disturbed and which most represented the mix of tree species, sizes, and crown conditions that typified the plant community. At most sites this was accomplished by laying out a plot 10 m wide by 50 m long, using a tape measure to ensure accuracy. The plots were oriented with the long axis parallel to the main slope. At one site, Plot 15, a grid 20 x 25 m was used. At each plot, the latitude, longitude, and elevation were measured using a portable Global Positioning System (GPS) instrument (Model AVD-55, Garmin Inst. Co, Kansas City, MO). Slope and aspect and other distinguishing characteristics were also recorded. A soil pit was dug in each plot and the soil characteristics were recorded. Composited soil samples from the A and B horizons were collected and submitted to the Soils Laboratory at UC Davis for analysis of pH, total N, SO_4, and P, and exchangeable cations, including Ca, Mg, and K. The A horizon is the surface soil layer, containing the highest amounts of organic material and in which biological and microbial activity is maximum. The B horizon is the sub-surface layer characterized by the accumulation of transformed organic and mineral materials leached from the A horizon.

All the trees in the plot > 10 cm DBH were identified, tagged and numbered, and the DBH was recorded for each. Tree heights and the length of the crown (from the top of the tree to the point of the lowest foliated branch) was measured with a clinometer (Model PM-5/1520, Suunto Corp., Finland). The crown base of each tree was measured along N-S and E-W directions. Notes were also taken that recorded unusual conditions in the size or irregularity of the tree crown. Branch samples were collected from six positions within the tree crown, lower, middle, and top on the N and S sides of the tree. Branch samples were collected with pruning poles to a maximum height of 6 m. For each branch, diameter at the base, total length, foliated length, and height and width of the foliated portion were recorded in the field.

The branches were then returned to the laboratory where leaf areas, fresh weight and oven dry weights of the foliage were recorded.

2. Measurement of Intercepted Light

Measurements of light transmitted through the canopy were taken at 10 locations within each sampling plot with a PAR ceptometer (Decagon Devices, Inc., Seattle, WA). At each point, the intensity of photosynthetically-active wavelengths of light (PAR) was measured at 8 compass points (N, NE, E, SE, S, SW, W, NW), and the measurements were averaged to produce a mean PAR for each of the 10 points within the plot. Similar measurements were made in a clearing or open area nearby, to establish the total incident PAR at that time. In addition, zenith angles to the horizon surrounding the plot were measured with a clinometer and these data were recorded for each plot.

In addition to these measurements on the biomass sampling plots, an intensive program of light transmittance measurements was conducted from 20 September to 8 October 1993 at 60 sites in the Huntington Lakes area east of Fresno. Thirty points were sampled on both the south-facing and north-facing slopes of the watershed. Associate site variables, such as tree species composition, elevation, slope, aspect, and angles to surrounding peaks were also recorded. The objective of this feasibility study was to assess the variability of foliar biomass over a small scale using the light-intercept technique.

B. Results

Tree mensuration data for all 29 biomass sampling plots are given in Appendix 1. Branch sample data, including foliar volumes, leaf area, and leaf fresh and dry weights, are given in Appendix 2. Light intercept data for all plots are given in Appendix 3, and soil sample analyses for all plots are given in Appendix 4. The data in these Appendices were delivered to the ARB on a 3.5" disk, included in the Final Report.

TASK 3
STATISTICAL ANALYSES AND COMPILATION OF FOLIAR BIOMASS DATA

A. Methodology - Determination of Foliar Biomass

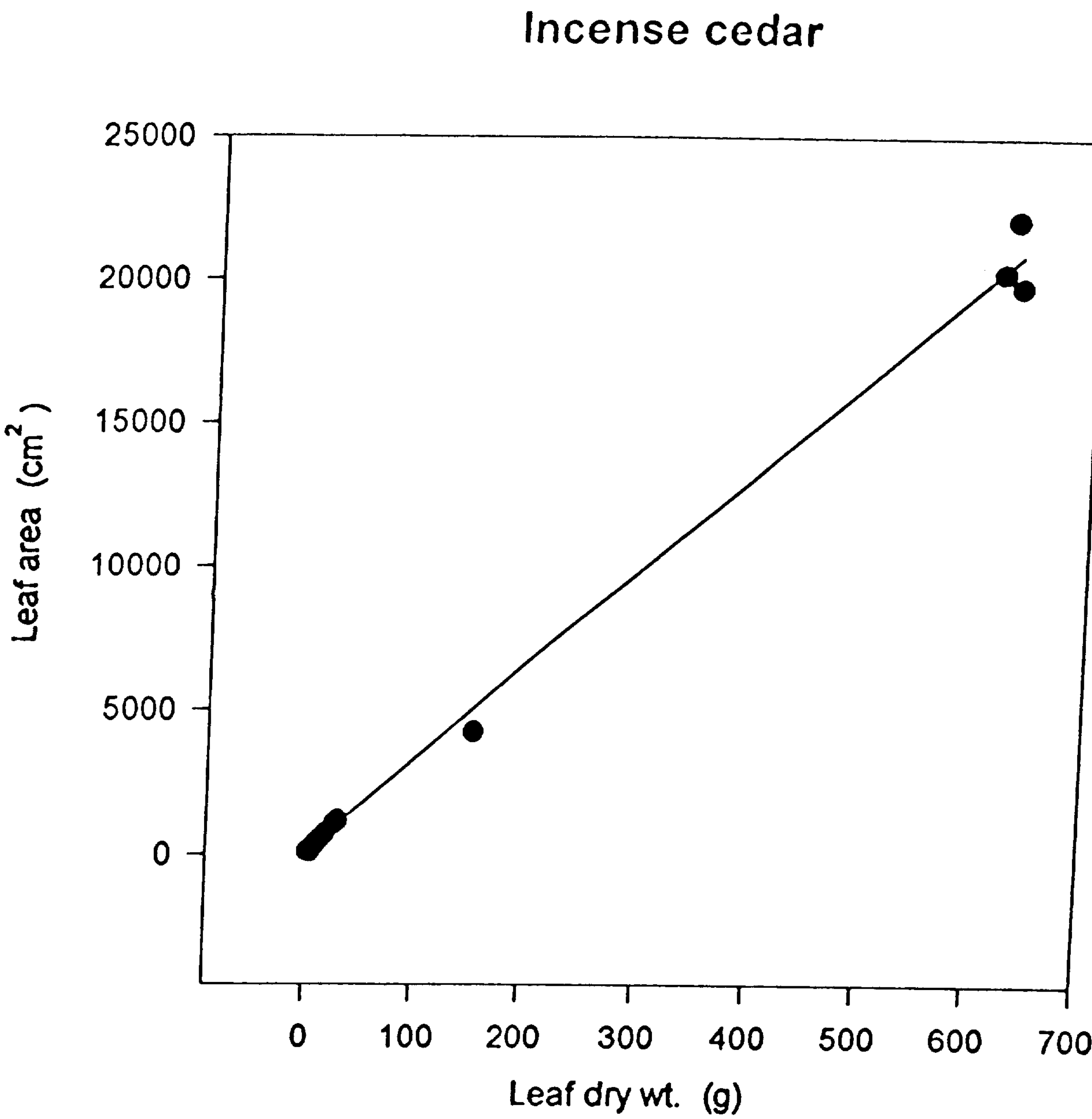
1. Allometric Relationships

Allometric relationships between leaf area and leaf fresh and dry weights were established for each of the major tree species on the biomass plots by means of regression analysis of foliage from the branch samples collected on the plots. These regression equations are given in Table 4. Leaf area and leaf dry weights were highly correlated in these species and regression coefficients typically were 0.90 or greater. The leaf area and leaf dry weight data used in these calculations are shown graphically for incense cedar (Fig. 8), white fir (Fig. 9), California black oak (Fig. 10), and for four species of pines (Fig. 11). Insufficient numbers of samples were available for the other tree species encountered on the biomass sampling plots to establish regressions between leaf area and leaf dry weight for all species. Equations for closely-related species were used instead. For example, the equation for canyon live oak (*Quercus chrysolepis*) (Table 4) was used to relate leaf area to leaf dry weight for blue oak (*Quercus douglasii*).

The regression equations between tree diameter (DBH) and foliar biomass used in this study were taken from the literature. For white fir, red fir, ponderosa and Jeffrey pines, and black and canyon oaks, the equations were derived from destructive harvesting of trees from the immediate area of the study, either in Sequoia/Kings Canyon National Park or from the western slopes of the southern Sierras. For the other species, the closest possible geographical reference or substitute species was used. The regression equations used to calculate foliar biomass from tree DBH used in this study are given in Table 5, together with the reference to the original report in the literature. The DBH data were also used to calculate the basal area for each species of tree on each plot. The basal area is a measure of the relative importance of each species in the tree community.

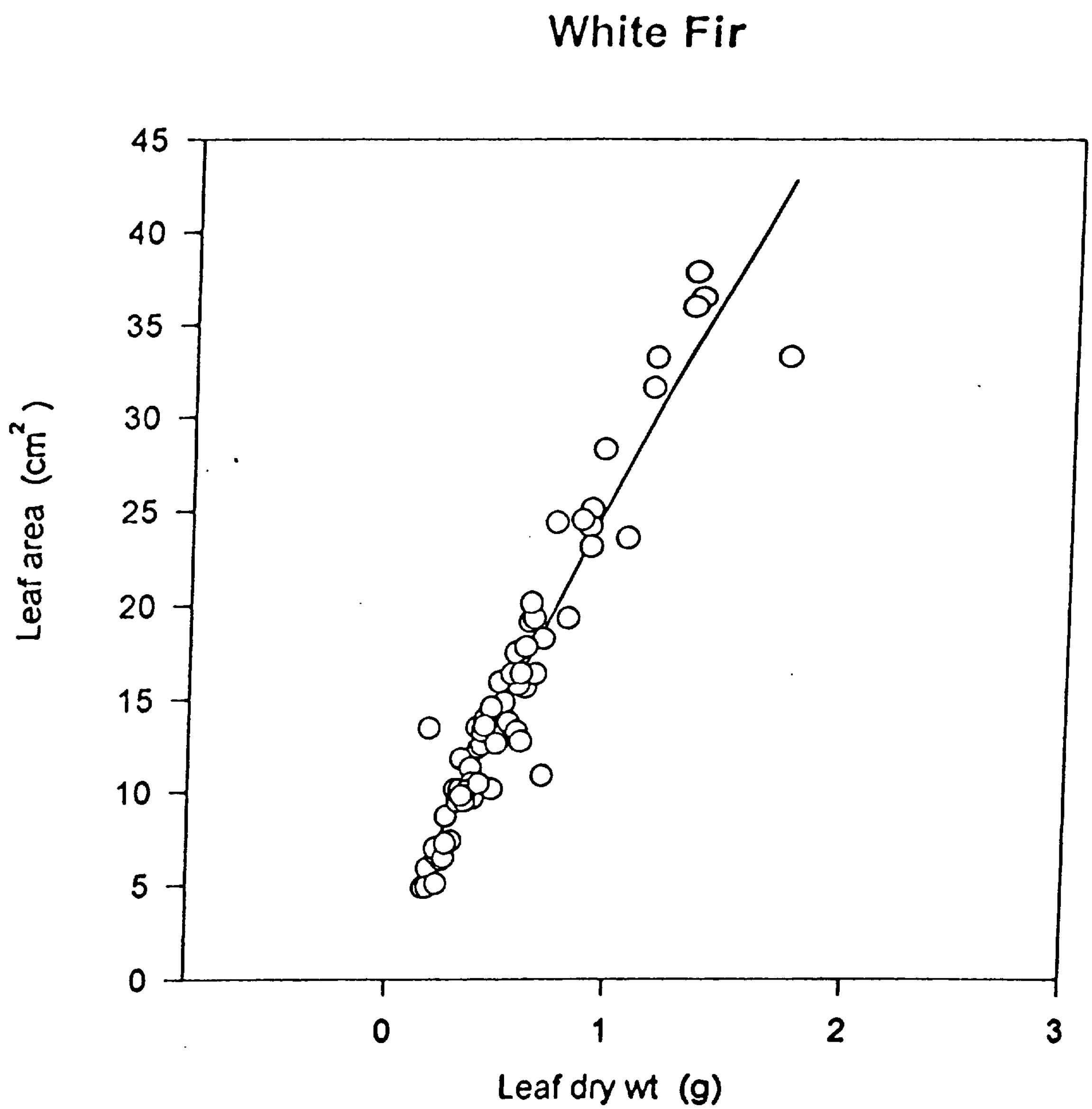
Table 4. Allometric relationships between leaf area and leaf dry weight, based upon branch samples collected on the biomass plots.

Abies concolor (White fir)	
Leaf area (cm^2) = 1.9625 + 23.9515 (leaf d.w., g)	R^2 = 0. 91
Abies magnifica (Red fir)	
LA (m^2) = -0.0695 + 0.0041 (leaf d.w., g)	R^2 = 0.92
Calocedrus decurrens (Incense cedar)	
LA (cm^2) = 15.0424 + 33.0870 (leaf d.w., g)	R^2 = 0. 99
Quercus chrysolepis (Canyon live oak)	
LA (cm^2) = 127.43 + 40.2074 (leaf d.w., g)	R^2 = 0.99
Quercus kelloggii (California black oak)	
LA (m^2) = 0.2655 + 0.0156 (leaf d.w., g)	R^2 = 0.83
Pinus contorta (Lodgepole pine)	
LA (cm^2) = -400.50 + 41.09 (leaf d.w., g)	R^2 = 0.98
Pinus jeffreyi (Jeffrey pine)	
LA (cm^2) = 90.60 + 29.36 (leaf d.w., g)	R^2 = 0.99
Pinus lambertiana (Sugar pine)	
LA (cm^2) = 180.37 + 50.20 (leaf d.w., g)	R^2 = 0.99
Pinus ponderosa (Ponderosa pine)	
LA (cm^2) = 451.42 + 34.21 (leaf d.w., g)	R^2 = 0.96



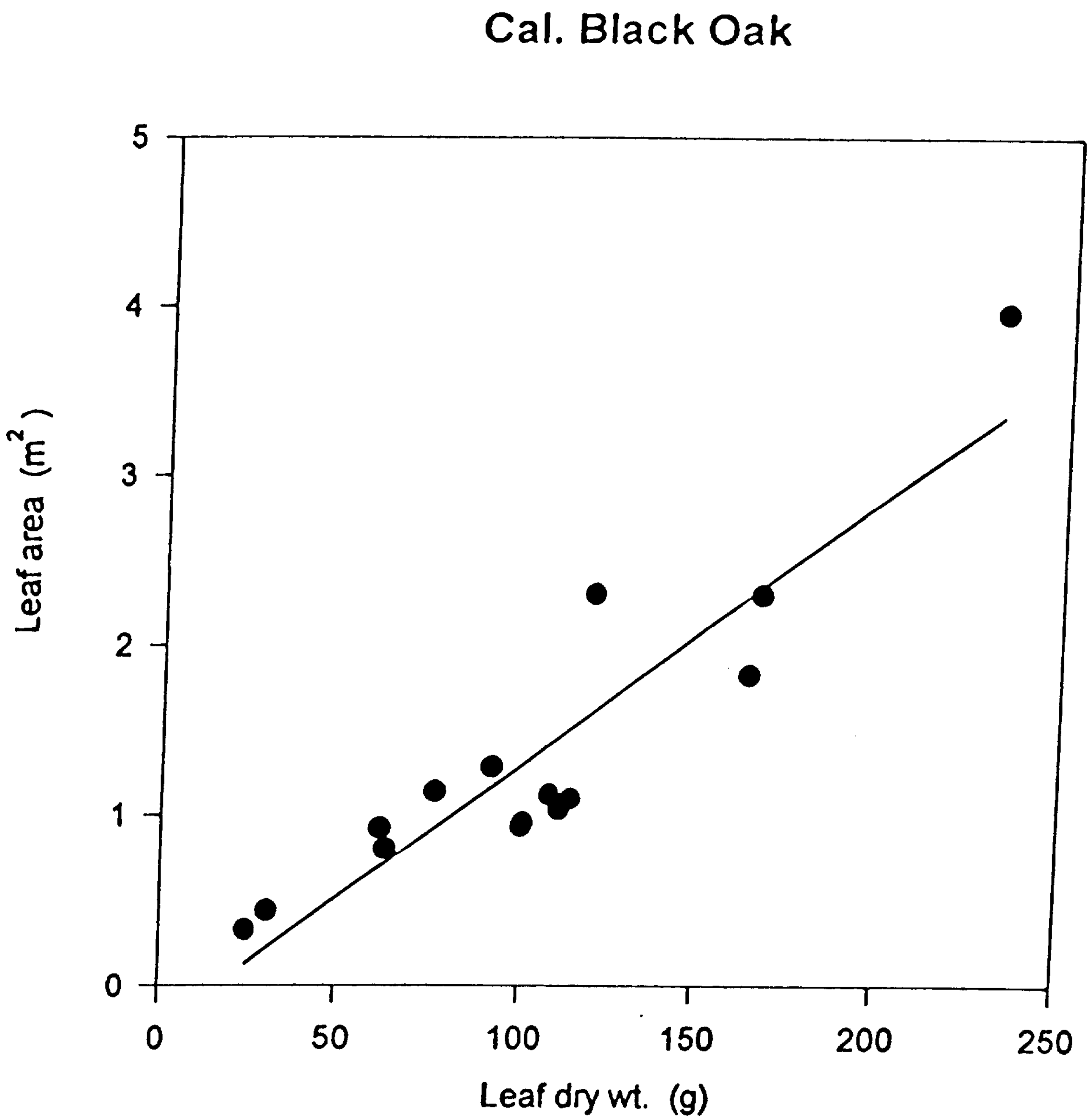
Leaf area (cm^2) = 15.0424 + 33.0870 (leaf d.w.) r^2 = 0.99

Figure 8. Allometric relationship between leaf area and leaf dry weight for incense cedar (*Calocedrus decurrens*), based upon branch samples collected from biomass sampling plots in the Sierras; n = 19.



Leaf area (cm^2) = 1.9625 + 23.9515 (leaf dry wt.) r^2 = 0.91

Figure 9. Allometric relationship between leaf area and leaf dry weight for white fir (*Abies concolor*), based upon branch samples collected from biomass sampling plots in the Sierras; n = 66.



Leaf area (m^2) = -0.2655 + 0.0156 (leaf dry wt.) r^2 = 0.83

Figure 10. Allometric relationship between leaf area and leaf dry weight for California black oak (*Quercus kelloggii*), based upon branch samples collected from biomass sampling plots in the Sierras; n = 14.

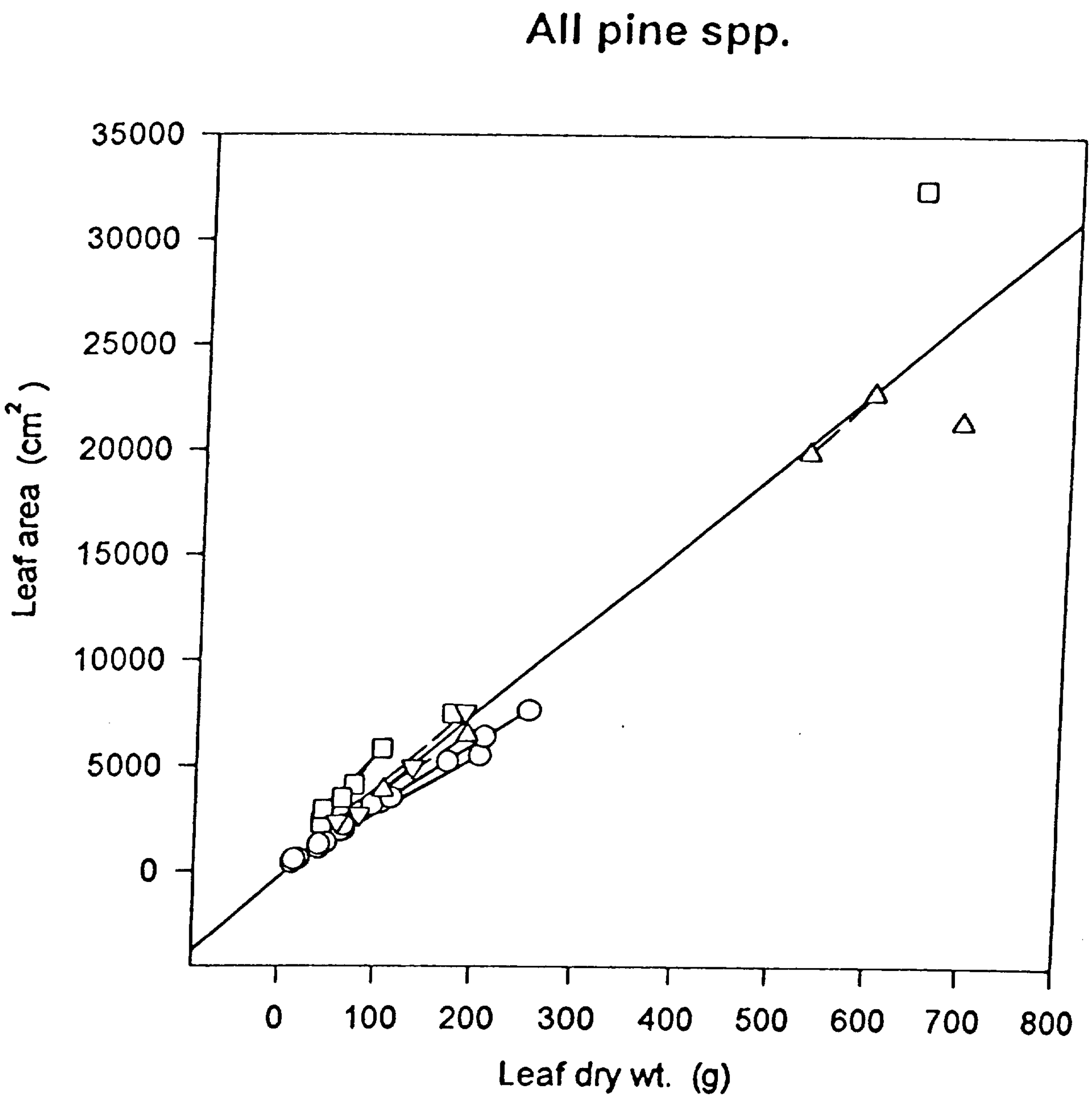


Figure 11. Allometric relationship between leaf area and leaf dry weight for all pine species (*Pinus* spp.), based upon branch samples collected from biomass sampling plots in the Sierras; n = 32.

Table 5. Allometric regression equations between foliar biomass and tree diameter (DBH) used to estimate leaf biomass for dominant trees in the Sierras.

Species	Location	Reference
Abies concolor:	Sierras	Westman (1987)
ln (biomass, g) = 1.89 (ln DBH, cm) + 3.82		
Abies magnifica:	Sierras	Westman (1987)
ln (biomass, g) = 2.93 (ln DBH, cm) - 0.13		
Calocedrus decurrens, no equation in literature; substituted *Thuja plicata*:	Montana	Kendall Snell and Brown (1978)
ln (biomass, g) = 1.36 (ln DBH, cm) + 5.31		
Pinus contorta, jeffreyi, lambertiana, ponderosa; for all Pinus spp. used *P. ponderosa*:	Sierras	Kittridge (1944)
log (biomass, kg) = 1.67 (log DBH, in) - 0.73		
Quercus chrysolepis, douglasii, lobata; used *Q. chrysolepis*:	Sierras	Kittridge (1944)
log (biomass, kg) = 2.66 (log DBH, in) - 1.36		
Quercus kelloggii, no equation in literature; substituted *Q. velutina*:	Tennessee	Rothacker et al. (1954)
log (N) = 1.86 (log DBH, in) + 2.44 N = no. of leaves; each leaf weighed 0.53 $\pm$ 0.28 g		
Cornus nuttallii, no equation in literature; substituted *C. florida*:	Tennessee	Rothacker et al. (1954)
log (N) = 2.05 (log DBH, in) + 2.86 N = no. of leaves; each leaf weighed 0.15 $\pm$ 0.05 g		
Aesculus californicus, no equation in literature; substituted *Carya tomentosa*:	Tennessee	Rothacker et al. (1954)
log (N) = 1.52 (log DBH, in) + 2.31 N = no. of leaves; each leaf weighed 0.82 $\pm$ 0.65 g		

2. Branch Volume to Crown Volume Relationships

This method for calculating foliar biomass used the relationship between the volume of foliage on branches sampled from individual trees and the volume of foliage in the tree crown as a whole. For those species whose shape approximated a cone, such as pines, firs, and incense cedar, the total volume in the tree crown was calculated by the hollow cone method; i.e., volume = outer cone volume - inner cone volume. The outside dimensions of the cone were the major and minor axes at the base of the canopy and the canopy height. The inside dimensions of the hollow cone were derived from measurements of branch samples, using the unfoliated length of the branch and the DBH of the trunk to determine the internal volume of the canopy not occupied by foliage. Thus, volume of foliage in a conical tree crown:

$$V = 1/12\ \pi\ abh - 1/3\ \pi\ r^2h$$

in which a and b are the lengths of the major and minor axes at the base of the canopy, h is canopy height, and r is the average length of the unfoliated branches plus the average radius of the trunk. Calculations for spherically-shaped canopies, such as the oaks, were similar, except that formulae for volumes of ellipsoids were substituted for those of cones.

Foliar volume of a branch sample was calculated from measurements of foliated branch length, width, and height:

$$V\ (\text{branch}) = \pi\ abh$$

Total foliage density within a branch was calculated as the total leaf surface area per foliated volume. The leaf surface area as measured by the leaf area meter was multiplied by π for cylindrical leaves, such as pine needles, or by 2 for flat leaves, such as the oaks. The mean foliage density per species was calculated from all available branch samples for that species and this mean foliage density was applied to the trees for which no branch samples had been collected. Total leaf area for each tree was calculated using the mean foliar density and the total foliated crown volume. Total leaf area was converted to biomass using the regression equations for leaf area/leaf biomass given in Table 4. These individual tree foliar biomasses were summed to produce a total foliar biomass for each species on each plot.

3. Light Interception Method for Estimating Foliar Biomass

Foliar biomass was estimated from light interception data using the method outlined by Norman (1988). Measurements of intercepted PAR under the tree canopy and PAR measurements at full sunlight were related to the total leaf area of the canopy using the relationship:

$$LAI = ((fb (1 - \cos \Theta) - 1) \ln (Ea/Ei) / 0.72 - 0.337 fb)$$

in which LAI is leaf area index, Ea = PAR outside the canopy, Ead = Par outside the canopy with the light sensor shaded, Ei = average PAR under the canopy, fb = (Ea-Ead)/Ea, and Θ = zenith angle. LAI was converted to leaf area by multiplying by the area of the plot (500 m^2). This total plot leaf area was proportioned to the individual tree species on the plots based upon the percent basal area for each species on the plot. The leaf area was converted to foliar biomass using the regression equations given in Table 4.

B. Estimates of Foliar Biomass

Biomass of foliage for all the trees on the sampling plots, estimated by the three independent techniques described above, is given in Table 6. Analysis of the data in Table 6 by individual tree species showed that for most species the three methods gave biomass estimates that were generally comparable (Table 7), although the method based upon crown volume relationships (Method 2) averaged higher than Method 1 (DBH) or Method 3 (light interception). For two species, however, these estimation techniques appeared to produce anomalous results. The crown volume method overestimated biomass of Jeffrey pine, particularly on Plot 15, where the Jeffrey pines constituted a small number (n = 9) of large, open-grown trees. The DBH method appeared to overestimate the biomass of red fir on those plots in which red fir was the dominant or co-dominant tree species, particularly on Plots 12, 20, and 21 (Table 6). Further analysis of the biomass data from Table 6 proceeded with the entire data set and also with the data from these plots estimated by these particular techniques removed from the data set.

Table 6. Foliar biomass for tree species on biomass sampling plots, estimated by three independent techniques: 1. DBH; 2. crown volume; 3. light interception.

			Foliar biomass (kg)		
Plot No.	Species	No. trees	DBH	Volume	Light
1	C. decurrens	25	590.3	1076.2	220.9
	A. concolor	6	39.7	97.0	20.5
	P. jeffreyi	1	48.5	62.9	20.4
	Q. kelloggii	3	85.1	32.1	6.8
2	A. concolor	2	42.0	69.8	44.2
	C. decurrens	34	596.5	436.9	454.8
	P. ponderosa	2	75.2	61.0	55.4
	Q. kelloggii	5	144.5	48.9	23.4
3	A. concolor	11	246.9	391.9	270.7
	C. decurrens	10	174.7	124.9	138.7
	P. jeffreyi	6	360.8	1847.7	322.8
	Q. kelloggii	6	41.1	15.6	6.9
4	A. concolor	12	222.2	280.0	515.4
	P. Jeffreyi	23	269.6	447.9	510.1
5	A. concolor	6	237.3	259.4	199.0
	C. decurrens	34	866.8	333.2	526.2
	P. lambertiana	1	11.2	5.2	4.5
	P. ponderosa	1	62.9	41.6	36.9
	Q. chrysolepis	3	52.4	9.2	26.2
	Q. kelloggii	7	110.2	40.8	14.2

			Foliar biomass (kg)		
6	A. concolor	28	2323.7	1813.5	1270.4
7	C. decurrens	1	17.7	57.8	22.0
	P. ponderosa	27	436.1	167.6	523.7
	Q. chrysolepis	1	3.4	8.9	3.5
	Q. kelloggii	17	66.7	62.9	17.6
8	A. californica	25	85.6	-	-
	Q. chrysolepis	20	777.2	886.8	484.2
9	A. californica	8	22.5	-	-
	Q. chrysolepis	5	16.6	53.0	15.2
	Q. kelloggii	44	431.5	850.9	101.9
10	A. concolor	15	1334.7	2057.1	910.4
	C. decurrens	6	159.9	604.9	79.0
	C. nuttallii	5	12.7	-	-
	P. lambertiana	1	123.0	282.3	40.0
11	A. concolor	19	2659.0	1549.9	883.7
12	A. magnifica	48	9949.8	4670.8	723.4
	P. contorta	1	88.0	47.0	6.3
13	A. concolor	1	10.2	6.6	10.7
	P. contorta	43	680.2	755.9	416.3
14	A. magnifica	38	382.2	631.6	392.2
	C. decurrens	1	28.9	37.8	36.4
	P. lambertiana	5	319.4	742.1	265.1
15	P. jeffreyi	9	289.3	210.6	259.0

			Foliar biomass (kg)		
16	A. concolor	1	74.1	89.0	95.5
	C. decurrens	7	186.2	533.5	173.7
	P. ponderosa	18	609.4	314.7	549.9
17	A. concolor	6	338.2	643.5	855.4
	P. ponderosa	3	7.4	3.6	13.1
	S. gigantea	12	-	-	-
18	C. decurrens	1	12.9	24.8	27.3
	P. lambertiana	2	31.5	22.7	44.0
	P. ponderosa	10	210.9	285.5	432.1
	Q. chrysolepis	1	0.2	0.9	0.3
	Q. kelloggii	1	19.7	67.7	8.9
19	C. decurrens	7	14.5	98.9	28.2
	P. ponderosa	24	326.5	164.1	613.9
20	A. concolor	42	1908.8	2577.5	503.0
	A. magnifica	4	2508.6	497.4	390.0
21	A. concolor	8	510.4	694.5	56.2
	A. magnifica	13	4326.6	614.5	280.9
22	C. decurrens	1	6.0	10.5	8.6
	P. jeffreyi	27	479.3	361.6	774.1
23	A. concolor	10	111.2	173.5	193.3
	C. decurrens	13	284.2	1576.1	357.6
	P. lambertiana	10	169.0	200.8	140.2
	P. ponderosa	6	366.1	447.4	445.5

			Foliar biomass (kg)		
24	C. decurrens	4	86.2	298.1	143.4
	P. ponderosa	11	224.0	182.2	360.3
	Q. kelloggii	4	178.6	164.3	63.0
25	C. decurrens	5	77.8	168.6	117.5
	P. lambertiana	2	43.5	73.5	43.3
	P. ponderosa	14	478.6	395.7	699.1
26	P. sabiniana	2	51.8	-	-
	Q. chrysolepis	7	202.4	219.2	142.6
	Q. douglasii	5	176.5	178.3	124.4
27	Q. douglasii	7	537.7	133.6	89.4
28	Q. douglasii	12	464.0	557.4	120.9
29	Q. douglasii	10	541.9	1189.5	113.5

Table 7. Average foliar biomass (Mg ha^{-1}) of dominant tree species of the western Sierra Nevada, estimated by three independent techniques; mean ± 1 standard deviation.

		Foliar biomass (Mg ha^{-1})		
Species	n	DBH	volume	light interception
White fir	167	14.36 (18.48)	15.28 (17.20)	8.32 (8.26)
Incense cedar	149	4.42 (5.40)	7.92 (9.06)	3.34 (3.34)
Jeffrey pine	66	5.80 (3.16)	19.30 (18.78)	7.54 (5.66)
Black oak	43	2.70 (2.62)	3.22 (5.66)	0.60 (0.68)
Ponderosa	103	5.60 (3.96)	4.12 (3.02)	7.46 (5.04)
Sugar pine	21	2.32 (2.32)	4.42 (5.54)	1.80 (1.94)
Canyon oak	19	3.50 (6.08)	3.92 (6.96)	2.24 (3.80)
Red fir	103	85.84 (82.04)	32.06 (40.92)	8.94 (3.84)
Lodgepole	47	7.68 (8.38)	8.02 (10.02)	4.22 (5.80)
Blue oak	34	8.60 (3.46)	10.30 (9.76)	2.24 (0.32)

TASK 4
EXTRAPOLATION OF BIOMASS ESTIMATES FROM SAMPLING PLOTS TO GRIDDED COVERAGE ACROSS THE STUDY AREA

A. Methodology

1. Multivariate Regression Analyses

The final phase of the biomass project involved the calculation of multivariate regression equations linking foliar biomass estimates on the sampling plots to GIS and environmental parameters that were associated with those estimates. The multivariate regression equations were then used to extrapolate foliar biomass across environmental gradients in forested areas of the foothills and mountains in the San Joaquin Valley Air Basin.

In the initial phase of data analysis scatter graphs were made for the biomass estimates, both on a per plot and on a per tree per species per plot basis. These scatter graphs were used to check for outliers and to look for patterns that would suggest curvilinear or multiple polynomial relationships. Some outlier data were identified as a result of this preliminary screening, and several plots were revisited and trees resampled to increase the precision of the original data set. In addition, plot 17 was eliminated from the data set. This plot was dominated by Giant Sequoia but as no biomass estimates could be made for this species, the data set from this plot could not be used. Preliminary data analyses also showed large variations in biomass among plots, due largely to variability in site quality across environmental gradients. A natural log transformation of the biomass data was used to equalize variances, to normalize distribution of residuals, and to enhance linear relationships between biomass and independent variables.

Preliminary statistical analyses using estimates of biomass for individual tree species to develop equations for the prediction of foliar biomass on a per species basis showed that this was not possible for this data set. First, the different tree species were present in only a limited subset of biomass sampling plots. White fir was present in the highest number of plots, 14. Ponderosa pine was found in only 10 plots. Red fir was present in only three plots. Second, the number of individual trees of each species sampled on each plot was highly variable. For example, white fir was the only species present on plot 6, where 28 trees were sampled. On plot 16, 26 trees were sampled, but only one white fir was found on the plot. Because of the high degree of variability in number of trees of each species per plot and because of the limited number of sampling plots in which the individual species were represented, regression equations between foliar biomass and independent variables were generally not significant. Data analysis proceeded using total foliar biomass per plot as the dependent variable.

The preliminary data screening also showed that the biomass estimates across plots differed significantly between conifer-dominated plots and oak-dominated plots. Environmental variables also divided along similar lines, as the oak-dominated plots were confined to the warmer, drier foothills and lower slopes of the Sierras. For these reasons, separate multivariate equations were fit for the conifer plots and for the oak plots.

2. Description of Independent Variables

The independent variables used in the preliminary data analyses are listed in Table 8. The variable list included site descriptors such as latitude, longitude, elevation, slope and aspect, maximum and minimum temperatures for each of the four seasons, and average precipitation for the last 10 years. Temperature and precipitation data were collected from the nearest long-term climatological station to the plot. Also included were site-specific soil characteristics, such as depth of litter layer, depth of A horizon, and soil chemical analyses for S, N, P, K, Ca, and Mg. These variables were of two types: (1) The site descriptors were derived from GIS coverages and thus can be accessed remotely for any point within the coverage area. (2) The site-specific soil characteristics were determined from soil samples collected on-site, and thus cannot be derived from GIS coverages. This distinction was maintained in the data analyses, so that two different sets of independent variables were included in the multivariate calculations: (1) the "GIS" set; (2) the complete set, including GIS and soil characteristics. Additional independent variables were derived from this original set by calculating interaction terms, such as precipitation by temperature, precipitation by N, or precipitation by the ratio of Ca to Mg. A final list of independent variables was determined by preliminary analyses of the data and by reference to the literature for potential interactions among variables. This list included approximately 75 variables, comprising original independent variables, curvilinear (quadratic) terms, and multiple interaction terms.

Table 8. List of independent variables used in multivariate regression calculations.

A. GIS- Derived:

Temperature: spring, summer, fall, winter max and min T (C)
Precipitation: mean annual ppt for last 10 years (cm)
Latitude, longitude, elevation (m), slope (degrees), aspect (degrees, N or S)

B. Site-Specific Soil Samples:

Litter depth (cm), depth of A horizon (cm)
Chemical analyses for A and B horizons:
N, SO_4, available P, K, Ca, Mg

C. Calculated Ratios and Interactions:

Ppt x temp
Ppt x N
Ppt x Ca/Mg
etc.

The independent variables were analyzed for principal components and factors to determine if the large number of variables could be replaced by a significantly reduced number of components or factors, or by a smaller sub-set of variables, one for each component or factor. This analysis showed that relationships among the independent variables were generally not strong enough to select representative components or factors. The exception was temperature, in which all independent temperature variables could be represented by a single factor. However, some initial regression analyses had shown that higher correlation coefficients were obtained with specific seasonal temperatures, relative to yearly mean temperature. Because of the loss of sensitivity to this key predictor variable for biomass if a factor were substituted, the original set of independent temperature variables was retained in the final multivariate regression analyses.

3. Multivariate Regression Analyses

Because of the large number of independent variables, backwards elimination regression could not be used. Consequently, stepwise regression analysis was used, with some restrictions on the maximum number of variables included in each equation. For the conifer plots, in which n = 22, a maximum of seven independent variables was allowed. For the oak plots, in which n = 6, only two variables were permitted to enter the equations. These restrictions were imposed to prevent overparameterization of the models. Three runs were conducted for each data set, at p = 0.05, 0.10, and 0.15; where p is the probability for entry or removal of a variable from the model. This analysis was conducted to identify potential candidate variables for inclusion in the multivariate model. In the final equation, each variable included was significant at p = 0.05 or lower. The final model was selected to meet all the following criteria: (1) all variables included were significant at p = 0.05 or lower; (2) the number of variables included did not exceed the limit imposed by the overparameterization restriction; (3) the model had the highest coefficient of determination (r^2); i.e,. had the highest predictive potential.

Multivariate regression models were computed using SAS for each of eight biomass data sets, including the three methods of biomass estimation and the geometric mean of the three biomass data sets, calculated separately for oak plots and conifer plots. In addition, separate equations were calculated using only the GIS variables, and the complete variable set including soil analyses. As a measure of the precision of the regression estimates, 95% confidence limits were calculated for all multiple regression equations that were statistically significant. The SAS statistical library provides 95% confidence limits for individual data points in a regression model. These confidence limits are equivalent to 95% confidence bands around a simple linear regression equation, and should be interpreted similarly. That is, 95% of the time the predicted biomass of a new plot randomly sampled from the same population of plots used in the original analyses will fall within these confidence limits.

B. Resu'ts

1. Multivariate Regression Equations

The coefficients of regression equations for predicting foliar biomass of conifers and oaks across environmental gradients in the SJVAB portion of the Sierras are listed in Table 9. Regression equations based upon the coefficients listed in Table 9 are given in Table 10.

Separate equations are given for each method of biomass estimation and for the geometric mean of the three methods. For conifers, elevation, temperature and precipitation interactions, and Ca to Mg ratios in the A horizon were the most significant variables for predicting biomass. As expected, the sites at higher elevations had higher precipitation and lower temperatures, which reduced evapotranspiration and increased the amount of water available for tree growth. This association between elevation and foliar biomass was most clearly demonstrated in the GIS regressions, in which elevation was the most significant variable, and in some cases the only significant variable, for prediction of biomass. Method 1, based on DBH, appeared to produce the best estimates of biomass relative to the other procedures and to the geometric mean of the three methods. The "best fit" regression equation, including all variables, accounted for 90% of the variability in foliar biomass across the conifer plots. The "best fit" regression equation based only on GIS variables accounted for 70% of the variability in biomass across the plots.

Although the regression equation relating foliar biomass as estimated by Method 1 to the GIS data sets had an R^2 of 0.703 (Table 9), the ability of this equation to predict foliar biomass in areas outside the original sample set was not known. An approximate test of the predictive ability of the regression equation, known as the "jackknife," was used to assess the predictive powers of the relationship between foliar biomass and GIS variables (L. Larsen, CARB, personal communication). The first step of the jackknife process consisted of calculations of new regression equations between Method 1 foliar biomass and GIS variables for each sub-set of 21 plots out of the total of 22 conifer plots. Thus, in turn, one plot of the 22 was left out of the biomass data set, and 22 new regression equations were calculated using the remaining 21 data sets. Each of these regression models was then used to calculate a predicted value for the excluded plot. The observed values for foliar biomass for the excluded plots were then correlated with the predicted values from the new regression equations. The correlation

Table 9. Summary list of coefficients for multivariate regression equations. Parameter coefficients are listed with ±1 standard error.

A. Conifer plots (n = 22)

Y = ln (total plot biomass, kg) — X = total variable list

Method	R^2	$p > F$	Significant variables	Coefficients	
1 (DBH)	0.904	0.0001	aspect	- 0.69	(0.10)
			summer max T	- 0.10	(0.04)
			ppt x spring min T	0.001	(0.0005)
			ppt x fall max T	- 0.004	(0.001)
			$(ppt)^2$ x Ca/Mg (A)	$6x10^{-6}$	$(5x10^{-6})$
			intercept	11.03	(0.92)
3 (Volume)	0.609	0.0006	elevation	0.002	(0.0004)
			$(ppt)^2$ x N (A)	- 0.002	(0.0001)
			$(ppt)^2$ x N (B)	0.004	(0.001)
			intercept	3.13	(0.74)
4 (Light)	0.815	0.0003	aspect	- 0.39	(0.13)
			depth of (A)	- 0.05	(0.016)
			P/K (A)	- 0.0006	(0.0001)
			Ca/Mg (A)	0.06	(0.015)
			winter min T	0.113	(0.03)
			ppt x fall min T	- 0.003	(0.0008)
			$(ppt)^2$ x (winter min T)^2	- $1x10^{-7}$	$(5x10^{-8})$
			intercept	7.85	(0.32)
Geometric mean	0.829	0.0001	elevation	0.001	(0.0002)
			K (B)	0.99	(0.29)
			P/K (A)	- $5x10^{-5}$	$(2x10^{-5})$
			Ca/Mg (A)	0.075	(0.018)
			$(ppt)^2$ x winter min T	- $1x10^{-6}$	$(3x10^{-7})$
			intercept	3.63	(0.44)

Y = ln (total plot biomass) — X = GIS variables list

Method	R^2	$p > F$	Significant variables	Coefficients	
1	0.703	0.0008	elevation	0.001	(0.0004)
			ppt x fall max T	- 0.0044	(0.0015)
			(spring min T)^2	- 0.044	(0.018)
			$(ppt)^2$ x winter min T	- $9x10^{-6}$	$(2x10^{-6})$
			$(ppt)^2$ x spring min T	0.0002	$(4x10^{-6})$
			intercept	5.88	(0.92)

Table 9 (continued)

3	0.306	0.008	elevation	0.001	(0.0004)
			intercept	4.88	(0.72)
4	n.s.		mean	6.50	(0.093)
Geometric mean	0.260	0.015	elevation	0.0008	(0.0003)
			intercept	5.39	(0.54)
B. Oak plots (n = 6)			X = total variable list		
1	0.947	0.012	slope	0.02	(0.004)
			SO_4-S (A)	- 0.125	(0.023)
			intercept	7.10	(0.22)
3	0.985	0.002	P(B)	- 0.015	(0.003)
			spring max T	1.31	(0.27)
			intercept	- 30.40	(7.63)
4	0.912	0.026	litter depth	1.26	(0.37)
			K (A)	- 4.68	(0.84)
			intercept	6.69	(0.46)
Geometric mean	0.979	0.003	K (A)	- 2.10	(0.21)
			SO_4-S (B)	0.068	(0.012)
			intercept	6.74	(0.18)
			X = GIS variable list		
1	n.s.		mean	6.28	(0.10)
3	0.968	0.006	spring max T	1.84	(0.29)
			(fall min T)^2	0.03	(0.01)
			intercept	- 46.89	(8.24)
4	n.s.		mean	5.14	(0.29)
Geometric	0.679	0.044	spring min T	0.44	(0.15)
			intercept	0.67	(1.81)

Table 10. Multivariate regression equations between estimates of foliar biomass on sampling plots in the Sierras and environmental variables. Y = ln (total foliar biomass, kg).

A. Conifer plots (n = 22)	
1. Total variable list, including soil analyses	
Method 1 (DBH)	Y = 11.03 - 0.69 (aspect) - 0.10 (summer max T) + 0.001 (ppt x spring min T) - 0.004 (ppt x fall max T) + 6×10^{-6} [(ppt)2 x Ca/Mg(A)].
Method 2 (volume)	Y = 3.13 + 0.002 (elevation - 0.002 [(ppt)2 x N(A)] + 0.004 $(ppt)^2$ x N(B).
Method 3 (light)	Y = 7.85 - 0.39(aspect) - 0.05 [depth of (A)] - 0.0006 [P/K (A)] + 0.06 [Ca/Mg (A)] + 0.113(winter min T) - 0.003 (ppt x fall min T) - 1×10^{-7} [$(ppt)^2$ x (winter min $T)^2$].
Geometric mean	Y = 3.63 + 0.001 (elevation) + 0.99 [K (B)] - 5×10^{-5} [P/K (A)] + 0.075 [Ca/Mg (A)] - 1×10^{-6} [$(ppt)^2$ x winter min T].
2. GIS variables list	
Method 1	Y = 5.88 + 0.001 (elevation) - 0.0044 (ppt x fall max T) - 0.044 [spring min $T)^2$] - 9×10^{-6} [$(ppt)^2$ x winter min T] + 0.0002 [$(ppt)^2$ x spring min T].
Method 2	Y = 4.88 + 0.001 (elevation)
Method 3	n.s.
Geometric mean	Y = 5.39 + 0.0008 (elevation)
B. Oak plots (n = 6)	
1. Total variable list	
Method 1	Y = 7.10 + 0.02 (slope) - 0.125 [SO_4 (A)].
Method 2	Y = - 30.40 - 0.015 [P (B)] + 1.31 (spring max T).
Method 3	Y = 6.69 + 1.26 (litter depth) - 4.68 [K (A)].
Geometric mean	Y = 6.74 - 2.10 [K (A)] + 0.068 [SO_4 (B)].
2. GIS variables list	
Method 1	n.s.
Method 2	Y = -46.89 + 1.84 (spring max T) + 0.03 [(fall min $T)^2$]
Method 3	n.s.
Geometric mean	Y = 0.67 + 0.44 (spring min T).

coefficient for observed vs. predicted biomass values was 0.242, indicating relatively poor ability of the full GIS model to predict foliar biomass of a plot not in the original data set.

The jackknife procedure also provided valuable information on the stability of the independent variables included in the multivariate regression equations. Elevation appeared in 17 of the 22 models, and various precipitation by temperature interactions appeared in 19 of the 22 models. These results showed the importance of elevation by itself or in combination with temperature and precipitation as the principal environmental determinants of variations in conifer foliar biomass. The precise elevation of the biomass sampling plots, or of any other point in the Sierras, can be determined with great accuracy, using standard GIS techniques. However, temperature and precipitation data must be extrapolated from scattered meteorological stations and may not accurately reflect conditions at the sampling sites. These results suggest that until future research provides greater understanding of the interactive effects of temperature and precipitation on foliar biomass, the simplest and most stable predictor of variability in conifer foliar biomass in the Sierras is elevation. The best-fit regression equation between conifer foliar biomass on sampling plots and elevation was:

$$Y \text{ (ln foliar biomass, kg)} = 4.88 + 0.001 \text{ (elevation, m)}.$$

This regression had an R^2 of 0.306, indicating that elevation by itself explained approximately 31% of the variability in foliar biomass across conifer sampling plots.

Regression equations for prediction of oak biomass are more difficult to interpret because only six plots were sampled and because environmental parameters did not vary substantially among the oak plots. Method 3, based upon crown to branch volume relationships, appeared to give the best estimates of biomass, particularly for the list of GIS variables. Soil parameters were the most significant variables in regression equations calculated from the total variable list. This may have occurred because these soil parameters had a greater range of variability across the oak plots than did temperature or precipitation parameters. When the soil characteristics were excluded, in the GIS regressions, oak biomass showed only a weak relationship to spring temperatures. Because of this relative lack of variability across oak plots, the best predictor of oak foliar biomass may be the mean biomass of the six oak plots.

2. GIS Analysis of Foliar Biomass

GIS was used to construct a digital database containing the relevant geographical information pertaining to the study area. GIS was also used for spatial analysis of the data and to construct maps of foliar biomass displaying the variability of biomass across elevational gradients in the Sierras. The multivariate regression analysis had shown that elevation was the principal GIS parameter that best predicted foliar biomass, so a high-resolution elevational grid map of the SJVAB was extracted from the DEM (Fig. 12). The resolution of the original grid was 250 m. Linear extrapolation techniques were then used to construct a new elevational grid with a resolution of 100 m that covered the study area in the Sierras. Foliar biomass in kilograms per hectare for each 100 m by 100 m cell within the grid was then calculated using the regression model $Y = 4.88 + 0.001$ (elevation). These biomass estimates in kg ha^{-1} were then summed over the 400 ha in each 2 x 2 km cell in the grid to produce an estimate of foliar biomass per 2 km cell. The geographical coordinates (latitude and longitude) of the centroid of each 2 km cell were attached to the foliar biomass estimates, and were used to construct a "look up" table, which listed the geographical coordinates and the estimated foliar biomass for each 2 km grid cell in the study area. A map showing the distribution of conifer foliar biomass per 2 x 2 km grid cell was constructed by classification of biomass estimates into a graded sequence from low (<2 kg x 10^6) to high (>25 kg x 10^6) across elevational gradients in the Sierras (Fig. 13). Foliar biomass on the lower slopes generally averaged 2 to 5 million kg per cell, increasing to 5 to 10 million kg per cell in the mixed conifer zone of mid-slopes, and 10 to 20 million kg per cell on the white and red fir dominated upper slopes.

These foliar biomass estimates for coniferous forest zones are higher than those previously reported for use in natural hydrocarbon emissions modelling in the SJVAB. The present research, based on broad-scale sampling of forest types across a range of environmental conditions, found that current forestry practices such as fire prevention and selective cutting of pines relative to less valuable species, have increased foliar density in these forests. In addition, biomass sampling in forests above 2000 to 2500 m indicated that these plots were largely dominated by dense white and red fir stands, with high foliar biomass density, rather than by mixed-conifer forest types of lower foliar density. Increased sampling of foliar biomass across a larger range of elevations and environmental conditions is needed to confirm these observations.

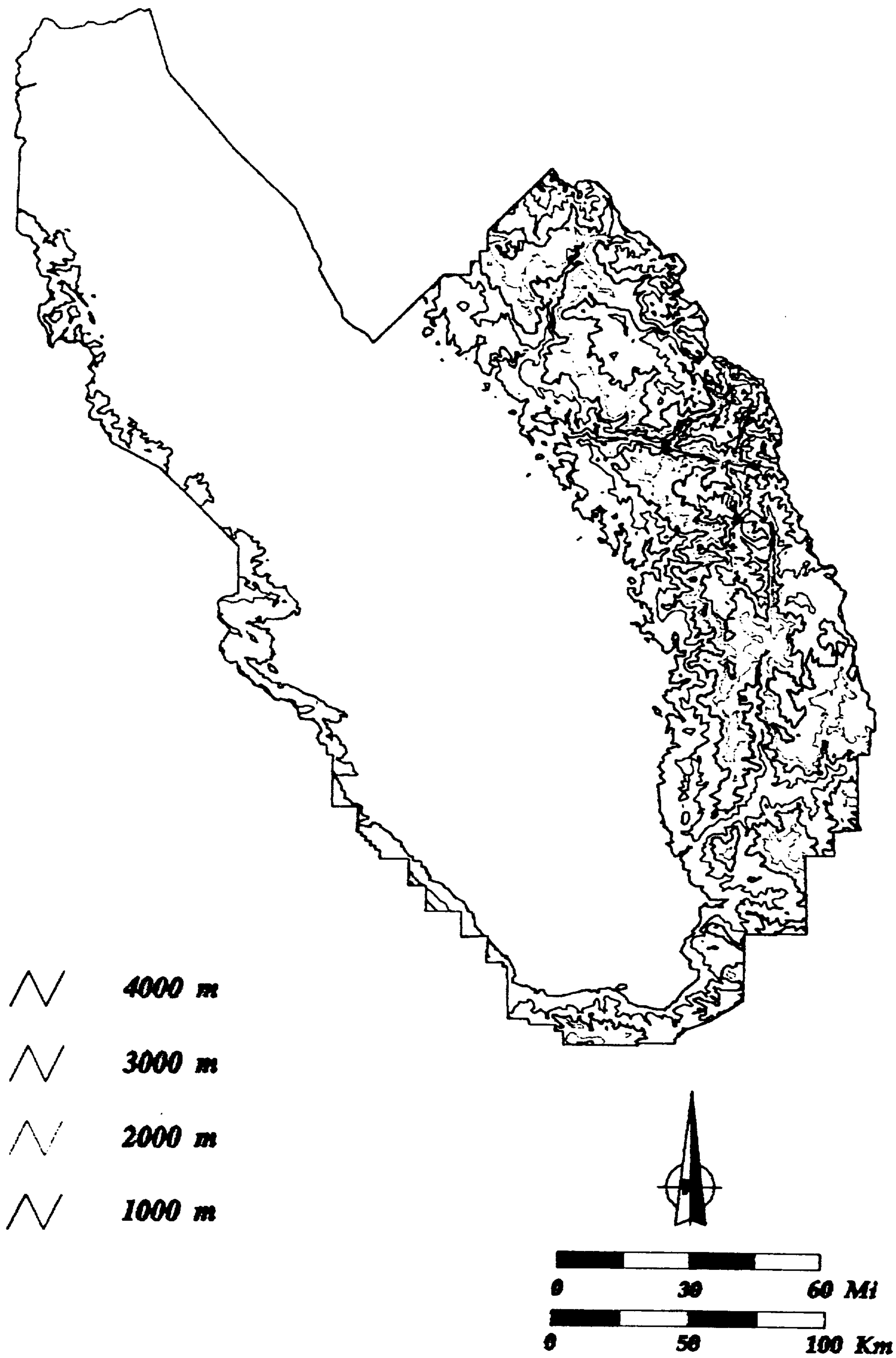


Figure 12. Elevational contour map of the SJVAB constructed from high-resolution DEM coverages.

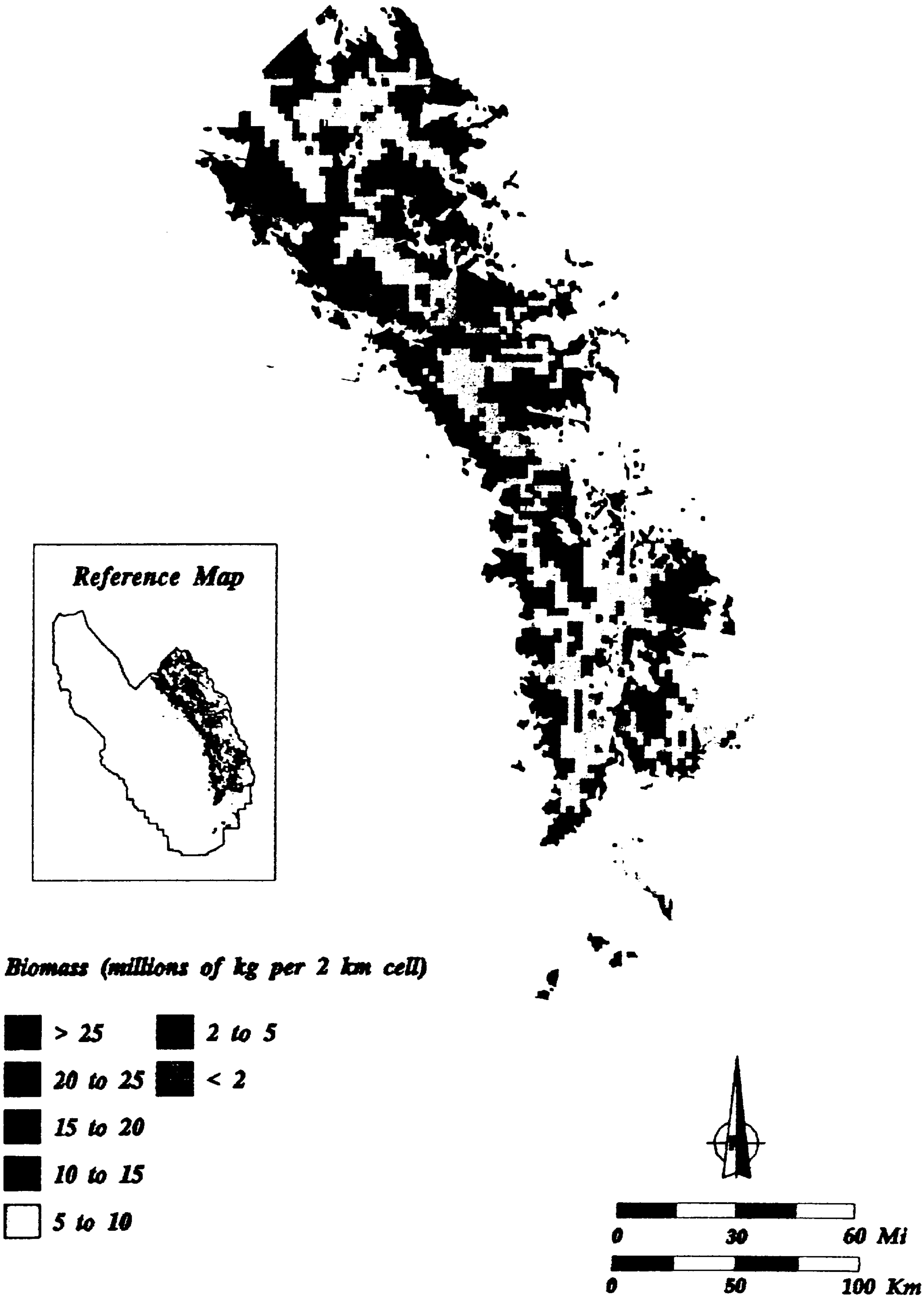


Figure 13. Foliar biomass estimates per 2 km grid cells of conifer and mixed conifer forest types in the SJVAB portion of the Sierras.

CONCLUSIONS AND RECOMMENDATIONS

1. Multivariate regression analysis was used to correlate foliar biomass on 22 conifer-dominated and six oak-dominated sampling plots in the SJVAB portion of the Sierras with a suite of GIS, environmental, and soil variables.

2. Foliar biomass on the sampling plots was estimated by three independent techniques: a. allometric relationship between tree diameter (DBH) and foliar biomass; b. ratio of branch sample volume, leaf area and biomass to whole crown volume, leaf area and biomass; c. light interception by the tree canopy. Biomass estimates among the three techniques were in general agreement, although on some plots one or more of the methods appeared to over or under estimate biomass by a significant amount.

3. The best-fit regression equations for foliar biomass of conifer-dominated plots included elevation, aspect, precipitation by temperature interactions, and soil fertility as significant variables in the equations. When soil fertility variables were excluded, elevation and various precipitation by temperature interactions were the significant variables in the equations.

4. Statistical analysis of the "best-fit" regression equation between foliar biomass on conifer-dominated plots and GIS variables using the "jackknife" technique suggested that this regression equation was a poor predictor of foliar biomass for plots not in the original data set. This procedure also showed that elevation was the most stable variable in the regression equations, along with various temperature and precipitation interaction terms.

5. Based upon these statistical analyses, the best available predictor of foliar biomass in conifer-dominated areas of the Sierras is elevation. The "best-fit" regression equation: Y (ln, foliar biomass, kg) = 4.88 + 0.001 (elevation, m) accounted for 31% of the variability in foliar biomass on conifer-dominated sampling plots.

6. The relation between biomass of conifer-dominated plots and elevation was used to construct a GIS-based map and "look up" table of the distribution of conifer foliar biomass per 2 x 2 km grid cell in the SJVAB portion of the western slopes of the Sierras.

7. Regressions between foliar biomass on oak plots and independent variables were generally not statistically significant because of the small number of plots ($n = 6$) and because the oaks occupy a relatively homogeneous habitat in the Sierra foothills, with little variability in meteorological parameters. The mean foliar biomass of the oak plots, estimated by DBH, was 11040 ($\pm$3180) kg ha^{-1}.

8. Future research to improve the accuracy of models of foliar biomass in relation to environmental variables should focus on better quantification of the effects of temperature and precipitation interactions on foliar biomass. This could be achieved by sampling in plots located over a wider range of temperatures and low, medium, and high average precipitation. More precise measurements of temperature and precipitation at the biomass sampling plots are also needed to improve the accuracy of these models of foliar biomass variability. Models of foliar biomass of individual tree species could also be obtained by sampling larger numbers of individual species across the complete range of their distribution in the Sierras.

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Glossary of Terms, Abbreviations and Symbols

Allometric	The numerical relationships among size and biomass of plant parts.
Ceptometer	Instrument for measuring intercepted light beneath a plant canopy.
Clinometer	Instrument for measuring angles; used to measure tree heights.
Edaphic	Site quality, with particular reference to soil conditions.
Extinction coefficient	The relative proportion of light intercepted by canopy leaf area.
Isoprene	Reactive hydrocarbon emitted primarily by deciduous leaves.
Lambert coordinate	Map coordinates corrected for the curvature of the earth.
Polygon coverages	Vector-based digital catalog of coordinates for geographic data base.
Sapwood	Area of tree stem used to conduct water and nutrients.
Terpene	Reactive hydrocarbon emitted primarily by coniferous foliage.
Zenith angle	Angle of the sun above the horizon.
ARC/INFO	Program for manipulating databases in a GIS system.
CALVEG	Map of California vegetation zones developed by California Department of Forestry and Fire Protection.
DBH	Diameter Breast Height, position at which tree diameters are measured.
DEM	Digital Elevation Model.
GIS	Geographic Information System.
GPS	Global Positioning System.
LAI	Leaf Area Index, ratio of ground area to canopy leaf area above.

NDVI	Normalized Difference Vegetation Index, ratio of spectral bands from satellite imagery used to differentiate vegetation types and to estimate productivity, based upon chlorophyll reflectance measurements.
SJVAB	San Joaquin Valley Air Basin.
PAR	Photosynthetically Active Radiation.

Abies concolor	White fir
Abies magnifica	Red fir
Aesculus californica	California buckeye
Calocedrus decurrens	Incense cedar
Cornus nuttallii	Western dogwood
Pinus contorta	Lodgepole pine
Pinus jeffreyi	Jeffrey pine
Pinus lambertiana	Sugar pine
Pinus ponderosa	Ponderosa pine
Pinus sabiniana	Gray pine
Quercus chrysolepis	Canyon oak
Quercus douglasii	Blue oak
Quercus kelloggii	California black oak
Quercus lobata	Valley oak
Sequoiadendron giganteum	Giant sequoia

Appendices

Appendices 1 to 5 are contained on two 3.5" disks that are attached to this report. Appendix 1 is the file TREE.WB1, which contains the complete tree measurement data set for each biomass sampling plot. Appendix 2 is the file BRANCH. WB1, which contains the complete data set on all branch samples collected on the plots. Appendix 3 is the file CEPTODAT.WB1, which contains the light interception measurements from each plot. Appendix 4 is the file SITESOIL.XLS, which contains the results from the chemical analyses of soil samples collected from each plot. A more complete description of each plot is contained in the file SITEDATA.WB1. These files are in Quattro Pro 1.0 format. Appendix 5 is the file GRIDBIOM.DOC, which is the look-up table of foliar biomass estimates for each 2 km by 2 km grid cell in the study area. Each cell is identified by precise latitude and longitude coordinates. This is a text file in Word for Windows 6.0 format.

Appendix 6 is a complete description of the technique for calculating the foliated volume of a tree crown from measurements of tree height, crown length and width, DBH, and foliated length of branch samples.

Appendix 1

Tree mensuration data from biomass sampling plots

(TREE.WB1)

Appendix 2

Branch sample data from biomass sampling plots
(BRANCH.WB1)

Appendix 3

Light intercept data from each biomass sampling plot
(CEPTODAT.WB1)

Appendix 4

Soil sample analyses from each biomass sampling plot
(SITESOIL.XLS)

Appendix 5

Foliar biomass on 2 x 2 km grid cells in the SJVAB portion of the Sierras
(GRIDBIOM.DOC)

Appendix 6

Procedures for calculating the foliated volume (V) of a tree.

I. Conically-shaped tree crown (Fig. 1).

1. Calculate volume of whole tree crown (V_1) using formula for an elliptical cone:

$$V_1 = 1/3\ \pi\ (a/2 \bullet b/2)\ h = \pi/12\ (a \bullet b \bullet h),$$

where V_1 = volume, a = width of base of crown, N-S, b = width of base of crown, E-W, and h = crown height.

2. Calculate internal crown volume (V_2) not occupied by foliage, using formula for right circular cone:

$$V_2 = 1/3\ r^2\ h,$$

where V_2 = volume of unfoliated crown, r = average unfoliated branch length in crown, and h = crown height.

3. Substract V_2 from V_1:

$$V = \pi/12\ a \bullet b \bullet h - \pi/3\ r^2\ h$$

II. Elliptically-shaped tree crown (Fig. 2).

1. Calculate volume of whole tree crown (V_1) using formula for an ellipsoid:

$$V_1 = 4/3\ \pi\ (a/2 \bullet b/2)\ h_1 = 1/3\ \pi\ (a \bullet b \bullet h_1),$$

where a = maximum crown width N-S, b = maximum crown width E-W, and h_1 = crown height.

2. Calculate internal crown volume (V_2) not occupied by foliage, using formula for an ellipsoid:

$$V_2 = 1/3\ \pi\ r^2\ h_2$$

where r = average unfoliated length of branches, and h_2 = unfoliated crown height.

3. Subtract V_2 from V_1:

$$V = \pi/3\ (a \bullet b \bullet h_1) - \pi/3\ r^2\ h_2$$

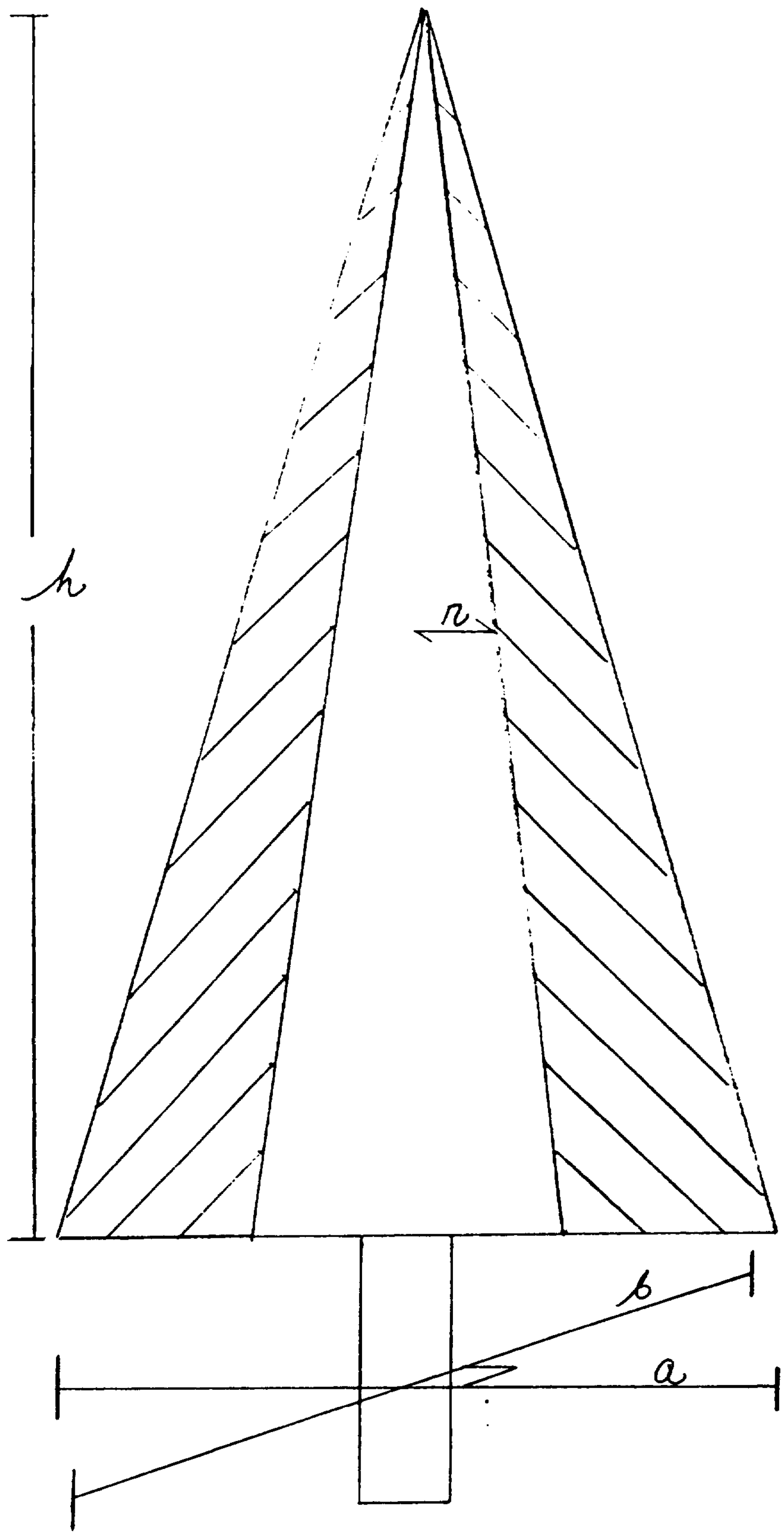

Figure 1. Diagram of conically-shaped tree crown showing dimensions used to calculate foliated volume.

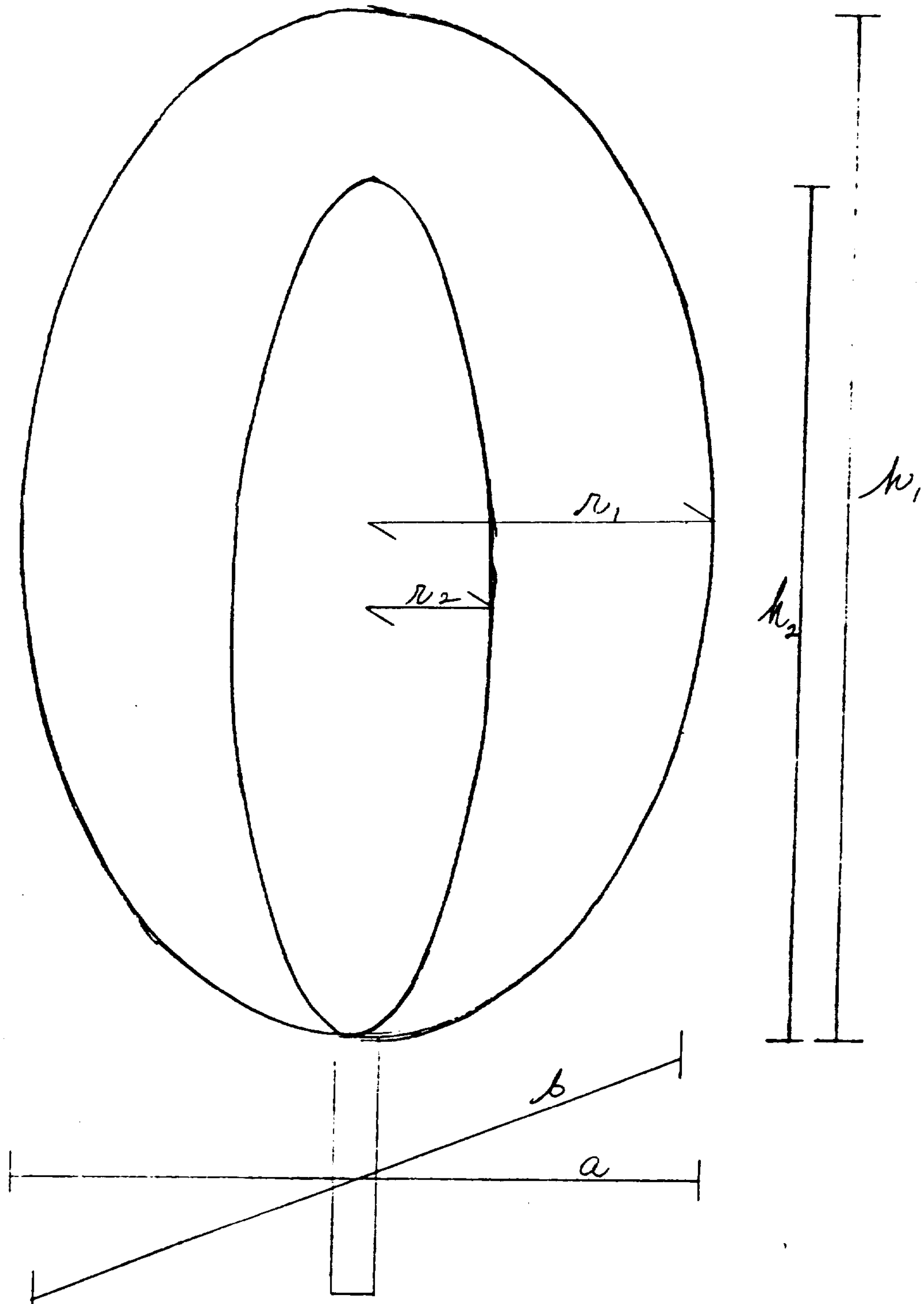

Figure 2. Diagram of elliptically-shaped tree crown showing dimensions used to calculate foliated volume.